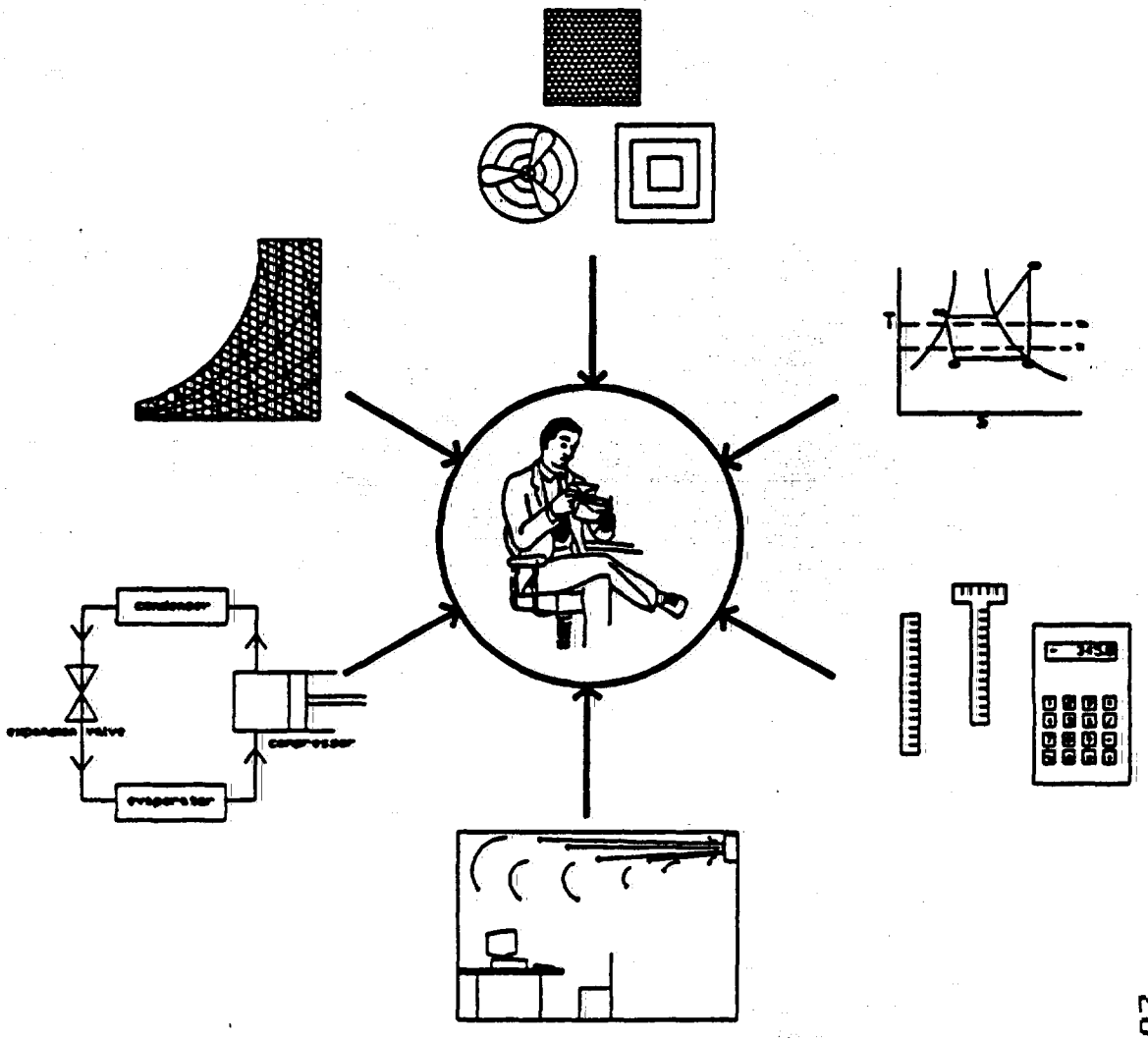
VENTILATION AND IAQ WORKSHOP

COORDINATED BY
ENVIRONMENTAL PROTECTION AGENCY'S
AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
AND THE
UNIVERSITY OF ILLINOIS'S
BIOENVIRONMENTAL ENGINEERING RESEARCH LABORATORY



2023687636

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

BIOENVIRONMENTAL ENGINEERING RESEARCH LABORATORY

VENTILATION AND IAQ
State-of-the-art, policy and research needs assessment

PURPOSE AND METHOD

Sixty experts from the buildings equipment, design, operation, maintenance, service, ownership and research fields cooperated with the EPA and University of Illinois in a September, 1993 workshop. Specific goals were:

* define state-of-the-art in building design and operation
* identify emerging technologies and trends which will influence building design and operation
* recommend policy changes for government, industry and professional societies that improve IAQ in practical, effective ways
* define and prioritize research needs.

IMPORTANCE OF IAQ

As a society we have become more conscious of our health and productivity. We want improved indoor environmental quality because we recognize the importance to our health. Also, we recognize that it is possible to achieve higher quality.

These growing concerns and expectations are international, and have led to rapidly growing and diverse international industry opportunities. Virtually the entire building industry is affected--designers, building materials and equipment manufacturers, builders, commissioners, building operators and owners, environmental quality consultants, energy suppliers, insurers, researchers and health professionals.

POLICY CHANGES NEEDED

Cooperation among the various professionals in the building industry and government is the most important change that can be made to help meet the opportunity for improved air quality in buildings. A lack of understanding and communication have resulted in minimal accountability for overall air quality within buildings.

2023687637

AGRICULTURAL EXPERIMENT STATION · ENGINEERING EXPERIMENT STATION · VETERINARY MEDICINE
University of Illinois at Urbana-Champaign · 1304 West Pennsylvania Avenue · Urbana, Illinois 61801
Phone 217 333-8220 · FAX 217 244-0323

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Codes and standards that define acceptable air quality are needed. The absence of standards discourages designers, manufacturers, operators and owners from achieving air quality conditions generally agreed to be reasonable economically and important to health. Failure of our building industry to advance with other important Western nations on this issue will result in our industry being economically uncompetitive and technologically obsolete in a business world rapidly becoming more international.

RESEARCH NEEDS TO OPTIMIZE AIR QUALITY

Research should become a more integral part of the building design-construction-operation process through active cooperation between industry and government. This cooperation will result in guidance and focus to research efforts and improve the technology transfer to industry. Multidisciplinary research team approaches are needed to deal with increasingly complex research challenges.

Research should proceed concurrently in: 1) air quality control--which includes ventilation, air cleaning and source management, 2) understanding air quality impacts and health effects and 3) risk assessment/economic optimization of systems. Failure to advance in any of the areas limits the usefulness of research advances in the other areas. Specific engineering research recommendations of highest priority are:

* Evaluation of impacts of alternative ventilation system design and management on IAQ

* Methods and codes to guide the design, installation, commissioning and operation of HVAC systems to achieve excellent IAQ

* More usable ventilation effectiveness definitions and practical means of field verification

* Advanced sensors and control techniques for achieving IAQ

* Models to predict air and contaminant movement in rooms.

2023687638

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

VENTILATION AND IAQ

State-of-the-art, Policy and Research needs Assessment

Prepared for the U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory

by
Russ Kulp and Les Sparks
AEERL Project Managers

and
J.B. Priest, Jon McLaughlin, Les Christianson
Alexander Zhivov, Mike McCulley, Glen Chamberlin,
Mike Tumbleson, Ronaldo Maghirang, Bryan Shaw,
Zhenhai Li, Jactone Arogo and Ruihong Zhang

Bioenvironmental Engineering Research Laboratory
University of Illinois

November 1993

2023687639

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

TABLE OF CONTENT

LIST OF FIGURES viii

LIST OF TABLES ix

EXECUTIVE SUMMARY 1

INTRODUCTION 4

CONSENSUS RECOMMENDATIONS 5

VENTILATION AND IAQ SYSTEMS ASSESSMENT 11

IAQ GAINS CONSCIOUSNESS 11

Energy conservation 11

Development in contaminant measurement techniques 13

Effects of exposure to new contaminants 13

IAQ DEFINITION 14

THREE DYNAMIC INFLUENCES ON IAQ 16

Outdoor environment 16

Internal sources 17

Occupants 18

Biological contamination 18

Building Materials and Furnishings 18

2023687640

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

HVAC Equipment 19

ROOM VENTILATION EFFECTIVENESS 21

METHODS - HOW AND WHY SYSTEMS ARE DESIGNED AND THEIR RELATIONSHIP WITH IAQ 25

STANDARDS AND GUIDELINES RELATED TO DESIGN 25

Codes 25

Standards and guidelines 27

Thermal comfort standards 27

IAQ standards and guidelines 30

Energy standards and guidelines 37

HVAC SYSTEM DESIGNS 37

General types of air conditioning systems 37

Air distribution systems within rooms 40

Duct systems 44

COMMISSIONING & TROUBLESHOOTING IAQ PROBLEMS 44

What is commissioning? 44

The commissioning process 45

Troubleshooting IAQ problems 47

Approaches to IAQ investigation 47

2023687641

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

OPERATION AND MAINTENANCE 49

Developing an IAQ management plan 50

Activities and responsibilities for IAQ managers 50

ECONOMIC COST ASSESSMENT 51

Ventilation and occupant satisfaction levels 51

Increasing ventilation rates in existing buildings - energy cost impacts 51

Increasing ventilation rates in existing buildings - system capacity impacts 52

Ventilation, occupant satisfaction levels and economics 52

Building life cycle costs 54

TECHNOLOGY - WHAT COMPONENTS ARE AVAILABLE? 56

COMPONENTS OF AN HVAC SYSTEM 56

Outdoor air intakes and building exhausts 56

Dampers and mixing plenum 57

Total minimum outdoor air control 58

AHU Media particulate air filters 60

Heating and cooling coils 61

Humidification/Dehumidification 61

Ducting 62

2023687642

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Plenums 63

ENVIRONMENTAL SENSORS AND CONTROL 64

Measurement of thermal comfort parameters 65

Air temperature 65

Mean radiant temperature 65

Air velocity 66

Humidity 67

Turbulence intensity 67

Flow patterns 67

Air exchange effectiveness 68

Measurement of IAQ parameters 68

Gases and vapors 68

Airborne particulate matter 69

Bioaerosols 70

Control strategies 71

AIR CLEANING AND FILTRATION EQUIPMENT 72

Filters 72

Air washers 75

Humidity control 76

Emerging technologies 76

2023687643

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

IAQ MODELS AND MODELING 78

HVAC INDUSTRY SURVEY 80

SURVEY METHODOLOGY 80

ISSUES ADDRESSED 81

FINDINGS 81

Researchers 82

System design 82

Industry weakness 83

Research 84

Designers 85

System design 85

Industry weakness 90

Research 90

Managers 91

Equipment Manufacturers 92

System design 94

Industry weakness 95

Research 98

WORKSHOP COMMENTS 98

2023687644

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Researchers 99

Designers 99

Utilities 100

Equipment Manufacturers 101

Owners and Managers 102

Commissioners and Balancers 102

Operation and Maintenance 103

REFERENCES 104

APPENDICES 117

1: Participants 117

2: Standards 125

2023687645

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

LIST OF FIGURES

Figure 1. Chronology of environmental concerns. 12
Figure 2. Department of Defense (1989) survey of what features of facilities are valued. 26
Figure 3. Life cycle cost relationships from B.O.S.T/National Bureau of Standards. 55
Figure 4. Initial capital costs. 55
Figure 5. Operation and maintenance cost for ten years. 55
Figure 6. Typical HVAC system components (EPA, 1991). 56
Figure 7. Particulate size of various contaminants 73
Figure 8. Technological/product/information flow within the HVAC industry. 80
Figure 9. How the four subject groups scaled IAQ as an issue. 82
Figure 10. Percentages of systems designed in the last 15 years. 86
Figure 11. IAQ and thermal performance of systems designed in the last 15 years. 87
Figure 12. How frequently designers are able to design and specify air supply, distribution and its control. 88
Figure 13. Factors that cause indoor air quality problems. 89
Figure 14. Results for factors that impact negatively on the air supply, distribution systems and controls. 89
Figure 15. HVAC system types managed by the building manager survey participants. 92
Figure 16. Percentage of IAQ and comfort complaints registered by managers. 93
Figure 17. Adjustments and modifications managers are able to make on their systems. 93
Figure 18. Results of ranked equipment criteria when designing new products. 94
Figure 19. Results from "other" design criteria not listed in survey. 95
Figure 20. What manufacturers focus on in product design and development. 96
Figure 21. Results of ranked order of preference, where new trends are identified. 96
Figure 22. Who manufacturers exchange information with, when designing products. 97
Figure 23. Percentages of how often manufacturers receive equipment feedback. 97

2023687646

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

LIST OF TABLES

Table 1. Energy conservation features in existing buildings (Korte, 1989). 13
Table 2. Causes of indoor air quality problems. 17
Table 3. Typical types of indoor VOCs and their sources. 20
Table 4. Design and maintenance shortcomings in problem buildings. 21
Table 5. Optimal and acceptable thermal comfort parameters in the occupied zone of the office spaces (SNiP 2.04.05-92). 31
Table 6. Coefficient of transition from normative air speed in the occupied zone to the maximum air velocity in the jet. 31
Table 7. Acceptable deviation of air temperature in the air jet from the normative air temperature in the occupied zone. 31
Table 8. Comparison of various standards/guidelines. 32
Table 9. Outdoor levels of air quality (CEC, 1992). 35
Table 10. Three levels of perceived indoor air quality (CEC,1992). 35
Table 11. Emission of heat, moisture and CO_2 by one person in the office space. 36
Table 12. Proportions of total life cycle costs from two different studies. 54

2023687647

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

EXECUTIVE SUMMARY

IMPORTANCE OF IAQ

As a society, we have become more conscious of our health and productivity. We want improved indoor environmental quality because we recognize its importance to our health. We also recognize that it is possible to achieve higher environmental quality. Air quality (the gases, aerosols and microbes in air) and thermal conditions (temperatures, humidities and air velocities) are critical parts of our indoor environment, largely determined by the ventilation and air conditioning system.

Rising public expectations for improved air quality already are being translated into a willingness by consumers to pay more for buildings that achieve this. Simultaneously, growing public irritation with buildings that do not provide good air quality has led to increasing amounts of litigation and demands for regulations and standards. Also, there is more concern for those who are more sensitive to IAQ problems, such as older members of our population and those who are ill.

These growing concerns and expectations are international, and have led to rapidly growing and diverse international industry opportunities. Virtually the entire building industry is affected--designers, building materials and equipment manufacturers, builders, commissioners, building operators and owners, environmental quality consultants, energy suppliers, insurers, researchers and health professionals.

POLICY CHANGES NEEDED

Cooperation among the various professionals in the building industry and government is the most important change that can be made to help meet the opportunity for improved air quality in buildings. A lack of understanding and communication have resulted in minimal accountability for overall air quality. A team approach is needed in the building industry where the various professionals work interactively to design, build and operate buildings and accept responsibility for quality and performance of the building. They must balance IAQ, energy consumption and other costs, which sometimes conflict. Along with this comes the need for education and training at all levels to ensure that systems will be designed, commissioned and operated in a manner that ensures proper indoor air quality.

Codes and standards that define acceptable air quality are needed. The absence of standards discourages designers, manufacturers, operators and owners from achieving air quality conditions generally agreed to be reasonable economically and important to health. Failure of our building industry to advance with other important Western nations on this issue will result in our industry being economically uncompetitive and technologically obsolete in a business world rapidly becoming more international.

2023687648

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Life cycle cost and value analysis is needed to guide decisions in the design, construction and operation choices in buildings. Many owners, designers, builders and operators are recognizing that the costs of achieving acceptable air quality generally are more than offset by the benefits of improved productivity and health for building occupants. However, we need ways to quantify economically these benefits (e.g., energy efficiency ratings used on appliances and automobiles) to help owners justify investments in IAQ.

TECHNOLOGICAL ADVANCES PROVIDE OPPORTUNITIES TO IMPROVE IAQ

Changes are underway in the way buildings are designed and operated. Innovators are developing more flexible building systems and components because this results in a more valuable and adaptable building. Cold air, individual work station, displacement and other ventilation technologies are being developed to give designers more flexibility in matching system performance to particular applications. Sensors and control advances give faster, more reliable responses, costs are declining and reliability is increasing. Computer innovations make possible much more systematic evaluation of alternatives both during design and operation. Air filtration and space cleaning technologies are continuing to improve. New materials are being developed that emit fewer air contaminants and that minimize the harboring of air contaminants.

At this time, it is possible to consider seriously the opportunities to enhance air quality beyond normal ambient levels. Already oxygen enrichment is provided in hospitals to aid recovery and air composition is altered to enhance growth and life of other biological organisms.

RESEARCH NEEDS TO OPTIMIZE AIR QUALITY

Research should become a more integral part of the building design-construction-operation process through active cooperation between industry and government. This cooperation will result in guidance and focus to research efforts and improve technology transfer to industry. Multidisciplinary research team approaches are needed to deal with increasingly complex research challenges.

Research should proceed concurrently in: 1) air quality control--which includes ventilation, air cleaning and source management, 2) understanding air quality impacts and health effects and 3) risk assessment/economic optimization of systems. Failure to advance in any of the areas limits the usefulness of research advances in the other areas. Specific engineering research recommendations of highest priority to achieve excellent IAQ are:

2023687649

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

* Impacts of alternative ventilation system design and management.

* Methods and codes to guide the design, installation, commissioning and operation of HVAC systems.

* More usable ventilation effectiveness definitions and practical means of field verification.

* Advanced sensors and control techniques.

* Models to predict air and contaminant movement in rooms.

2023687650

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

INTRODUCTION

PURPOSE

Indoor air quality (IAQ) is a broad topic--our focus was on the relationship between ventilation and IAQ. Specific goals were;

* Define the state-of-the-art in building design and operation.

* Identify emerging technologies and trends which will influence building design and operation.

* Recommend policy changes for government, industry and professional societies that improve IAQ in the most practically effective ways.

* Define and prioritize research needs.

SPONSORSHIP

The Air and Energy Engineering Research Laboratory of the U.S. Environmental Protection Agency and the Bioenvironmental Engineering Research Laboratory of the University of Illinois sponsored this effort. The Department of Energy and the National Institute for Science and Technology cooperated to define the purpose and methods.

PARTICIPATION

This report was compiled and reviewed by experts selected from the spectrum of professionals who are knowledgeable about IAQ--designers, building materials and equipment manufacturers, builders, commissioners, building operators and owners, environmental quality consultants, energy suppliers, insurers, building researchers and health scientists. Professionals from all these fields were interviewed and relevant technical literature and product information was reviewed to prepare a working document. This working document was reviewed, edited and expanded to include the "Consensus Recommendations" by those listed in appendix 1.

2023687651

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

CONSENSUS RECOMMENDATIONS

The following items were identified by participants and agreed by consensus as important current problems (knowledge limits), policy needs, emerging trends and research needs. Participants worked in small groups of approximately 10 people; then ideas were combined and discussed by the entire group of 60 participants[1].

KNOWLEDGE LIMITS THAT AFFECT CURRENT BUILDING DESIGN AND OPERATION

Lack of definition of "acceptable indoor air quality" is the most critical information lack causing the frequent failure to achieve IAQ in buildings. Freedom from gases, particles and microbials in excess of amounts normally present in outdoor air generally is agreed to be "clean air". The issue of acceptable IAQ is further complicated by questions about other environmental factors (e.g., temperature, humidity, air velocity and light levels) that interact with IAQ and affect people's health and productivity.

Experts tend to agree about reasonable levels of classes of indoor air pollutants (e.g., the American Council of Government and Industrial Hygienists has long had detailed standards for industrial work places). The impacts of air quality vary among people; therefore, a complete understanding of air quality will not be possible. Acceptable IAQ must be defined if we want this to become part of standard building and equipment design and management practice within the industry.

Four other important knowledge limits were identified, essentially equal in priority and that correspond with research and development needs, that make it difficult to achieve and maintain high IAQ in buildings.

1) Predictability of air flow and ventilation effectiveness for alternative ventilation systems and methods in realistic buildings.

2) Availability of reliable and affordable measurement techniques and sensors for IAQ.

3) Understanding of release and absorption of air contaminants onto surfaces within buildings, and consequently the potential for control through cleaning and other management strategies.

4) Methodology and equipment to filter and clean contaminants from room air and surfaces.

[1]The entire group of participants is listed in Appendix 1. This includes 60 people invited experts, plus 14 staff from the U.S. Environmental Protection Agency and the University of Illinois who managed and facilitated the workshop.

2023687652

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

POLICY RECOMMENDATIONS FOR IMPROVING INDOOR AIR QUALITY IN U.S. BUILDINGS

Quality buildings require a team approach--and team responsibility. Building professionals must work together to achieve high IAQ, and recognize that effective solutions require a balancing of space, air quality, energy and economic needs. This kind of effort can begin with cooperation among the various professional societies and government agencies that are concerned with building technology on issues as basic as defining acceptable IAQ.

Codes and standards that define acceptable air quality are the most important current policy needs. Lack of standards makes specification of building design and management practices that will achieve high indoor air quality difficult. Further, this lack discourages innovations in the equipment, materials, maintenance and buildings industries that will provide improved IAQ.

General acceptance of "life-cycle costing" for designing and managing buildings is the second most critical policy change needed in the U.S. buildings industry to achieve higher indoor air quality. Closely related is the need for ways to quantify value of IAQ--the equivalent of "energy efficiency ratings" for air quality. Clearly, there are health and productivity economic and societal benefits from achieving higher IAQ. However most people involved in the financial decisions--banks, builders, owners, insurance companies, business tenants and the public--see IAQ as a qualitative issue and do not have accepted methods for assigning economic value to IAQ.

Another major policy need is effective technology transfer and communication among the varied specialists with expertise on buildings and air quality. This is especially needed for the maintenance and cleaning of buildings. Too often buildings are not commissioned properly to adjust equipment properly and solve problems prior to building occupancy. This attention to maintaining equipment properly and checking the quality of the internal environment should continue throughout the life of the building--continuous commissioning. The people responsible for the maintenance and management of the buildings need training on IAQ.

Cooperation is needed among government agencies, industry and public institutions to conduct the research and develop the technologies needed to improve IAQ. Despite the importance of IAQ and public concern about ensuring safe indoor environments, federal agency support of research of IAQ has been limited. Further, the research support that has been provided has focused on understanding the health effects and there has been much less effort toward developing technologies that can solve or minimize IAQ problems.

Lastly, perspective and stability are needed in policies related to IAQ. Too frequently policies, remedial actions and research are guided by emotional reactions to issues that receive spectacular press

2023687653

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

coverage. The consensus vision by experts on ventilation and indoor air quality issues in this report can help provide the perspective and stability needed to guide most effectively our policy and research efforts.

EMERGING TRENDS THAT WILL AFFECT VENTILATION AND INDOOR AIR QUALITY

Participants were asked to identify trends that were already emerging in some parts of the world, that were under development by industry or that were foreseen in the near future as likely to emerge and have an impact on ventilation and IAQ in buildings. The emerging trends identified by the participants were not ranked in priority, significance of impact or timing. The trends fit into the following broad categories.

Technological advances

* Alternative ventilation strategies emerging include:
  - micro-climate control,
  - displacement ventilation,
  - under-floor air supply distribution,
  - dedicated (fixed) outside air supply,
  - separate occupant control of temperature and ventilation rate,
  - cold air distribution systems.

* Flexible HVAC systems that are responsive to building use changes.

* Gas and particulate IAQ sensors suitable for both building evaluation and control applications.

* Computer based control and expert systems that are reliable and cost effective in managing HVAC equipment to optimize IAQ, energy conservation and other environmental aspects of buildings.

* Database on emission rates from IAQ pollution sources.

* Advanced/enhanced filtration technology for dusts, gases and microbes.

* Models to predict air and contaminant distribution in ventilated spaces and to predict the effectiveness of delivering fresh air to occupants.

2023687654

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Building industry changes

* More common use of an integrated approach to indoor environmental quality by occupants, managers, designers and builders.

* Greater awareness of the importance of IAQ and knowledge of how to monitor and manage IAQ.

* Proof of performance and performance contracting.

* More HVAC and IAQ education and training for those involved in operations and maintenance.

* International competitiveness becoming a factor in building design and operation.

* Awareness of the importance of cleaning and other means of source control to achieve IAQ; emphasis on building cleaning as a health and productivity issue.

* Emphasis on building flexibility and adaptability to changing occupancy and uses in the design phase; recognition of the higher value of flexible buildings; development of equipment and furnishings that are more flexible by the building component industry.

* More awareness of source and sink characteristics of building materials and on the importance of cleanability; choosing materials partially on the basis of their impact on IAQ in building design and renovation.

* Designing for simplicity and individual controllability.

* More common monitoring of IAQ and other aspects of the indoor environment.

Regulations and policies that are currently causing changes

* Consideration of the potential impacts of future legislation, specifically, related to Occupational Safety and Health Act reform (and possible expansion), broadening of IAQ legislation, regulation of environmental tobacco smoke and mandating energy efficiencies.

* Existing legislation and policies on clean air, health, disability accommodation, the use of CFCs and energy efficiency requirements.

* Increasing awareness of risk assessment in evaluating the impacts of future legislative and

2023687655

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

regulatory actions.

* Consideration of the threat of more litigation related to issues and evaluation of the potential risks of poor IAQ in buildings.

RESEARCH PRIORITIES FOR INDOOR AIR QUALITY

Research important to IAQ covers a broad range of engineering, health and related expertise and pertains to source control, cleaning and ventilation technologies. The focus of this state-of-the-art assessment and research needs prioritization was on ventilation and IAQ issues. Consequently, we have defined and prioritized the ventilation related research needs, without attempting to prioritize these needs in comparison to other research needs (e.g., health effects or source control). We do emphasize that ventilation related research is an equally high priority with the other major topics of "sources", "air cleaning", "economics" and "IAQ impacts (i.e., health and productivity effects)". Lastly, we have defined the research needs in these other major topic areas as perceived important and as having an impact on ventilation issues.

Ventilation research priorities in rank order from highest

1) Evaluate different system designs for their impact on IAQ.

2) Develop checklists, protocols, standards and codes which guide and regulate the design, installation, commissioning, operation and maintenance of HVAC systems.

3) Define ventilation effectiveness and the method of its verification in the field.

4) Develop advanced sensors and control techniques (self diagnostics, less expensive, more rugged and more accurate).

5) Develop adequate models to predict air and contaminant distribution.

6) Validate ASHRAE Standard 62-1989 to see if it results in good IAQ.

7) Measure the effectiveness of outdoor air supply strategies.

2023687656

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Sources

* Compile database on emission rates of contaminants by different sources.

* Develop practical means and guidance on the control of sources by cleaning methods, source location and material selection.

Air cleaning

* Evaluate the costs and benefits of recirculation with air cleaning versus supplying larger amounts of outdoor air.

* Improve gaseous and aerosol filtration technologies.

IAQ impacts on health and productivity

* Determine the health effects of long term low level exposure to pollutants.

* Evaluate the tradeoffs and relationships among IAQ, productivity, health, comfort and energy requirements.

* Determine the impact of HVAC system maintenance on IAQ.

Economics and optimization

* Compare the performance (including IAQ) and costs of alternative HVAC strategies and systems.

* Develop cost/benefit information related to IAQ; include risk assessment in the analyses.

2023687657

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

VENTILATION AND IAQ SYSTEMS ASSESSMENT

Indoor air quality (IAQ) has become an important public issue. Its popularity has grown as we increasingly recognize that IAQ affects our health, productivity and comfort. Since the advent of modern society, 90% of our time is spent indoors and our welfare is measured and reported quantitatively as IAQ. Words used to describe the scientific performance of IAQ are subjective words like good, poor or excellent that hold meaning even to those not interested in the scientific field. As researchers and designers in this field we must agree on quantitative descriptions to remove much of the miscommunication and misunderstanding surrounding IAQ. The ultimate objective of a successful environmental system is to provide for the comfort and welfare of the occupants and prevent an accumulation of unpleasant and/or harmful pollutants.

IAQ GAINS CONSCIOUSNESS

The importance of IAQ and other environmental concerns has increased significantly during the last two decades (Figure 1). The consciousness of IAQ can be attributed to several developments. Energy conservation, as a result of concern for future energy resources, is cited most often as the single most contributing factor. However, IAQ concerns have contributed to publicity, improved contaminant measurement technology and new contaminant exposure awareness, as well as more energy conservation efforts.

The current trend in addressing IAQ issues is for all partners to take a defensive position and analyze their risk. For the industry, risk management strategies for IAQ fall into two categories: regulatory and nonregulatory (Axelrad and Maroni, 1993). Regulatory risk management activities include bans on chemicals and other products, exposure limits, emission rate limits, labeling requirements, building design standards and operation and maintenance requirements. Nonregulatory strategies include guidelines, development of incentives, model building codes, training and information dissemination and outreach.

Energy conservation

Energy conservation regulation methods have contributed to IAQ problems directly and indirectly through changes in reduced ventilation rates, control systems, building construction techniques and new ventilation techniques. For the last twenty years, the uncertain future of energy resources due to shortages of fuel oil, passive and active solar energy, development of nuclear power technology and trade imbalances and embargoes has raised national and international resource conservation efforts. Prior to the last two decades, designers' and managers' priorities were to maximize comfort with little emphasis on energy consumption. Within the United States, energy conservation is an integral part of our current

2023687658

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

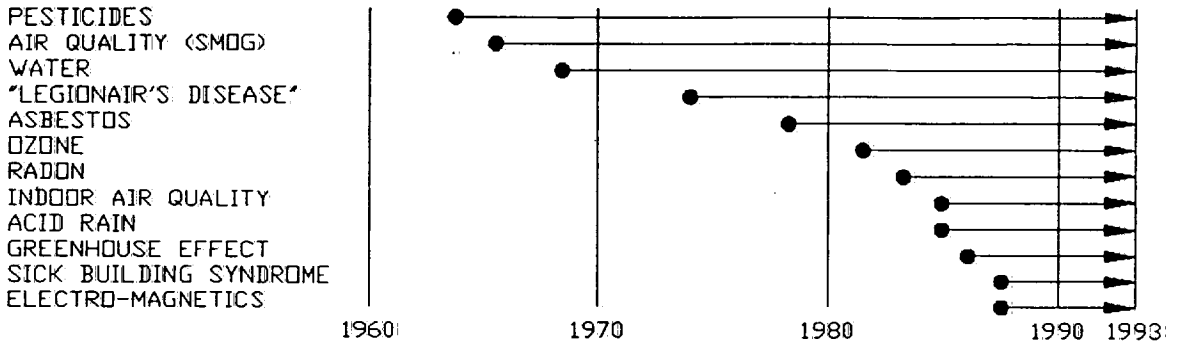


Figure 1. Chronology of environmental concerns.

executive branch's conservation initiatives. Recent world events have perpetuated these energy resource concerns as Persian Gulf instability continues to provide uncertainty for world oil supplies. British Thermal Unit (BTU) legislation proposed by the Clinton administration during 1993 would have applied even more economic pressure affecting conservation efforts and indirectly, IAQ. Consequently, energy conservation standards have addressed and should continue to address, impacts on indoor air quality (Talbott, 1990). The Department of Energy performed a survey in 1986 (Korte, 1989) that examined the energy conservation features of existing commercial buildings far more extensively than any of its previous surveys (Table 1). Fifty-two percent of commercial buildings have at least one of the HVAC energy conservation features outlined in Table 1.

Due to many of these features, source control and contaminant removal must be addressed directly. In the past, poor HVAC designs and source control methods benefitted from the less tight building practices and higher ventilation rates. By employing more energy conservation practices, it is necessary to identify pollutants and their sources and determine their control and removal specifically.

Public perception

Law suits and "sick buildings", coined in the 1980's to denote buildings with high incidents of "Sick Building Syndrome" (Walkinshaw, 1993) have become common documentaries and subjects in our communication world. These highly visible and usually minimally researched articles have gained large publicity. Publicity identifying a problem building usually reacts more quickly than research and analysis can be completed. Lawsuits and liability issues also are results of public perception and publicity.

2023687659

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Partnering, a new legal approach to the prevention of construction disputes through interdisciplinary team building, is one of the new creative alternatives being explored as a possible vehicle to involve, prior to construction, those responsible for building operations and maintenance (Clavier, 1993). Public perception is the driving force that lead to the politics of the Montreal Protocol and its recent revisions in Copenhagen, Denmark. While controversy around the results of ozone depleting refrigerants still lingers, domestic and international politics forge ahead to phaseout dates for chlorinated fluorocarbons (CFC) and HCFC before the issues are scientifically agreed upon. For better or worse, public perception is an important part of IAQ and potential future regulations.

Table 1. Energy conservation features in existing buildings (Korte, 1989).

HVAC conservation feature	Buildings with feature	Installed at time of construction	Added before 1980	Added 1980 to 1985	Added in 1986	Added to save money
Variable air volume	547,000	374,000	61,000	85,000	26,000	118,000
Preventive maintenance program	2,076,000	1,258,000	318,000	375,000	124,000	564,000
Waste heat recovery	149,000	89,000	11,000	34,000	14,000	51,000
Energy management system	205,000	66,000	8,000	94,000	37,000	132,000
Time clock thermostat	64,000					
Economizer cycle	17,000	53,000	23,000	71,000	11,000	97,000
Other HVAC features	76,000					

Development in contaminant measurement techniques

Air velocity and contaminant measurement techniques with data acquisition systems have become less expensive during the last 10 years. Advances in computers and digital information transfer have allowed for extensive field studies and experimental analysis that have been revolutionary in contaminant recognition and exposure. Radon measurement and testing is the most publicized contaminant that has been identified through new computerized measurement capabilities. These capabilities also have created concerns about scientific credibility and experimental repeatability.

Effects of exposure to new contaminants

Diagnosis of health effects due to IAQ problems often is difficult because many symptoms of IAQ problems are similar to those of other disorders (Axelrad and Maroni, 1993). Commonly, symptoms and health complaints reported by the office workers are diverse and not specific enough to identify readily

2023687660

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

the causative agent (NIOSH, 1989). Common health related complaints include: eye irritation, dry throat, headache, fatigue, sinus congestion, skin irritation, shortness of breath, cough, dizziness, nausea, sneezing and nose irritation. The effects of indoor air pollutants span the range from mild irritations and headaches to cancer and increased mortality. Source factors include an increased number of synthetic materials that emit chemical pollutants and cause physiological stress. The World Health Organization (WHO) defined "Sick Building Syndrome" (SBS) and indicated it is widespread, occurring in nearly 30% of new and remodeled buildings (WHO, 1987). Researchers are accumulating information from investigations, leading to the resolution of the "Sick Building Syndrome" problems (Walkenshaw, 1993).

Due to changing building materials and construction techniques as well as to changes in work habits during the past two decades, the new effects of indoor air pollutants on human health have been identified and classified into the following categories (Axelrad and Maroni, 1993):

1) Building Related Illness (BRI) refers to an illness brought on by exposure to building air,
2) Sick Building Syndrome (SBS) refers to a series of acute, nonspecific complaints that occur in high prevalence among occupants of certain buildings,
3) Multiple Chemical Sensitivity (MCS) is a syndrome in which individuals report sensitivity to a variety of chemicals in indoor air, each of which may occur at very low concentrations,
4) Certain groups of people, such as children, the elderly and allergic individuals are more susceptible to environmental pollutants than others.

SBS has been experienced even though exposures to gases, vapors and dusts have been minuscule when compared to exposures of factory workers to similar substances (Peterson, 1992). Susceptibility to pollutants is the subject of much active research. Standards for the evaluation of indoor, nonfactory environments are beginning to emerge. Peterson (1992) believes in a few years, many standards will probably be available. Today, for instance, Japan uses 150 $\mu g/m^3$ as the indoor standard for respirable particulate matter and 10,000 $\mu g/m^3$ for carbon monoxide. Several countries have proposed or adopted indoor standards for formaldehyde and a few other materials. No one yet knows just how SBS is caused or what materials should be blamed (Goyer, 1990).

IAQ DEFINITION

There are several definitions of indoor air quality that are used by various groups. The Sheet Metal and Air Condition Contractors' National Association, SMACNA, (1990a) defines IAQ as "the nature of air that affects the health and well being of occupants." The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Standard 62-1989) interprets acceptable indoor air quality as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not

2023687661

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

express dissatisfaction." This definition incorporates the concept of health used by the World Health Organization, which defines health as "a state of complete physical, mental and social well being and not merely the absence of disease or infirmity." The WHO definition includes three qualities: threshold limit value, cubic feet per minute per occupant and percent dissatisfied.

The ACGIH, 1992 developed the concept of indoor air quality for industrial spaces based on threshold limit values (TLV) for different contaminants to which workers can be exposed forty hours per week over long time periods without developing adverse health effects. Depending on the amount of time a worker is exposed to a contaminated environment, there are three TLV categories. For a normal eight hour workday and a 40 hour work week which will produce no adverse health effects for nearly all workers, the time weighted average (TWA) is used. If workers are to be exposed to chemicals which have both acute and chronic toxic effects, a 15 minute time weighted average called a short term exposure limit (STEL) is used. The third limit is a ceiling (TLV-C), which is a concentration that should never be exceeded when workers are present.

However, these threshold limits are not considered applicable to residential, commercial and public environments. Until recently, industrial hygienists have been skeptical about applying TLV's to non-industrial environments. The Indoor Environmental Quality (IEQ) Committee of the American Industrial Hygiene Association (AIHA) has come to favor alternative approaches (generally non-numerical criteria) to resolve IAQ issues in non-industrial workplaces (Hodgson et al., 1993).

Several European guidelines on indoor air quality are based on new units for describing odor: the olf and the dicipol. The olf is the unit of odor source strength, dependent on the emission rate of malodorous substances from the source. The decipol is the perceived odor level, dependent on the concentration of inhaled malodorous substances. The concentration of air pollution depends on the pollution source and the dilution caused by the ventilation.

Pollution from a human being was chosen as the reference because it is well known and considerable knowledge is available as to how bioeffluents are perceived by other human beings. Since Pettenkofer (1858) and Yaglou (1936), the human being has been considered the main pollution source in offices, assembly halls and other nonindustrial buildings. This line of thought is reflected today in ventilation standards all over the world. Typically, ventilation requirements are defined as per occupant (Fanger, 1988a).

Future approaches for indoor air quality evaluation may combine contaminant source strengths and perceptions of indoor air quality by the occupants. IAQ, thermal characteristics (temperature, humidity and velocities) of the air and other environmental variables may be incorporated into a "total environmental quality" rating.

2023687662

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

THREE DYNAMIC INFLUENCES ON IAQ

IAQ can be evaluated as the result of three dynamic interactions and simultaneous relationships. The resulting IAQ is related to the outdoor air quality and quantity supplied, internal pollution sources within the ventilated environment and the pollution associated with the elements of the heating, ventilating and air condition (HVAC) system. These influences vary with time. Considering the strengths of these three sources and their dynamics can help in designing for adequate indoor air quality.

The impact of the three previously mentioned interactions can be seen in studies carried out by NIOSH (Crandell, 1987) and the Health and Welfare Canada (Kirkbride et al., 1990). These studies identified the various causes of indoor air quality problems (Table 2). Both reports were based solely on a population of reported sick buildings. The data in Table 2 summarized one primary problem for each investigated building; however, field results rarely identify a single problem in a building (Collett et al., 1993). Typically, several inadequacies are identified within a building that contribute to occupant discomfort and ill health.

Outdoor environment

The outdoor environment directly affects the IAQ by being a possible pollutant source and dictating the required amount of outdoor air needed to remove contaminants. Factors such as outdoor temperature, humidity and pollutant concentrations can change rapidly, so systems must be able to react quickly to compensate for these changes. Contamination from sources outside the building was determined to be a major problem in ten percent of the NIOSH investigations (Table 2). While outdoor air generally is less polluted than the system return air, treatment becomes necessary depending upon the outdoor contaminant levels. Problems with motor vehicle exhaust, boiler gases and previously exhausted air occurred as a result of improperly located exhaust and intake vents or periodic changes in wind conditions. Other outdoor contamination problems include contaminants from construction or renovation, such as dust, asphalt vapors and solvents.

While most systems are designed for maintaining thermal comfort, few can modify their operation based on internal changes in contaminant levels which are affected by pollution in the outdoor air supply. The dynamics of adjusting outdoor air supply rates to varying outdoor contaminants are just beginning to be investigated.

2023687663

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Table 2. Causes of indoor air quality problems.

Cause:	NIOSH[1] (%)	HWC[2] (%)
Inadequate ventilation	52	52
Indoor contaminants	16	12
Outdoor contaminants	10	9
Building fabric	4	2
Biological contamination	5	0.4
No problem found	12	24

[1]NIOSH survey conducted in 484 buildings.
[2]HWC survey conducted in 1,362 buildings.

The building site itself can be a source for pollutants such as moisture and radon. Radon entry into large buildings can be caused by the effect of either ventilation air or infiltration air (Menetrez and Kulp, 1993). In building design, the key roles influencing radon entry from soil is the design and operation of the ventilation system, which affect pressures driving bulk airflow through soil and the design and construction of the building substructure, which controls the degree of movement between the air in the soil and the air in the building. Infiltration of radon in large buildings increases when buildings are at negative pressure relative to outdoors.

Internal sources

Contamination of indoor air is common from sources associated with activities inside the building. About 12 to 16% of IAQ problems were related to indoor generated contaminants (Table 2). Possible sources within the building include building materials, emissions from office equipment and maintenance and occupant activities that use or generate chemical products or other pollutants. The building itself, including furnishing, carpeting and ventilation system, usually is a more important polluter than the occupants (Thorstensen et al., 1990).

There are various types of indoor air pollutants and they fall into the following categories: particulate, microbiological, chemicals (inorganic and organic) and combustion products. Particulates include dust, asbestos and pollen. Microbiological includes fungi and bacteria. Chemicals encompass volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAH) and ammonia. Combustion

2023687664

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

products consist of particulates, tobacco smoke and fuel combustion gases, such as NOx and SOx. A more detailed analysis of some indoor pollutant sources follows.

Occupants

The metabolism processes of plants and animals are chemical reactions, which result in the release of gases into the local environment. The net balance uptake of O_2 and release of CO_2 by animals and conversely the uptake of CO_2 and release of O_2 by plants need to be taken into account in many applications where IAQ is of interest.

Biological contamination

Contamination with biological agents, such as molds, yeast or bacteria can occur in ventilation systems and/or building furnishings. From 0.4% to 5% of the investigations have some type of microbiological contamination (Table 2), which commonly has resulted from water damage to carpets or furnishings, standing water in ventilation system components or improperly cleaned and maintained humidification systems.

Building Materials and Furnishings

Indoor sources for VOCs include building materials, interior furnishings, consumer products, heating and cooking appliances, as well as bioeffluents of occupants (Table 3; Sterling, 1984). Contamination from building materials and products was the major problem in 2 to 4 percent of the building investigations. Synthetic building materials may emit volatile organic compounds. For example, formaldehyde can off-gas from urea-formaldehyde foam insulation, particle board, plywood and some glues and adhesives commonly used during construction.

VOC sources can be characterized in terms of production of VOCs in the sources and mass transfer mechanisms involved in the emission processes. Production of VOCs vary with the sources. VOCs emitted from heating and cooking appliances are produced from combustion of fuels. VOCs emitted from building materials, furnishings and consumer products come into the indoor environment with the original sources. VOCs also can be produced by the microbial actions on the material surfaces in rooms, HVAC systems and on dust in the air. The mass transfer mechanisms involved in the emission processes are also source specific. For the sources such as building materials (particle board, plywood, insulation foams), furnishings (carpets) and some consumer products (air fresheners), emission of VOCs from the sources into the air involves in-material transfer and surface evaporation. For other sources (e.g., paint, cleaners, floor wax, pesticides), emission of VOCs is by surface evaporation or surface desorption.

2023687665

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Sexton et al. (1989) studied formaldehyde exposures in 470 mobile homes. Formaldehyde concentrations were "well-mixed" inside the homes over a 1 week period; average formaldehyde levels ranged from 0.07 to 0.09 ppm. Formaldehyde levels appeared to be decreasing in homes manufactured since 1980, probably due to the use of low formaldehyde emitting building materials. Of the 470 homes studied, 31% were found to exceed the 0.1 ppm maximum concentration recommended by the ASHRAE, AIHA and EPA.

HVAC Equipment

HVAC equipment has a significant effect on IAQ, as it serves to dilute or remove pollutants, distribute air and condition it as necessary. The types of equipment and the ways the equipment is operated and maintained influence air distribution and equipment emissions, which affect indoor air quality.

In a global effort to conserve energy, modern building design has favored tighter structures with lower rates of ventilation, potentially offering more control due to lower outside air rates and reduced fuel costs. This has created a source of IAQ problems. NIOSH (Crandell, 1987) and HWC (Kirkbride et al., 1990) determined that inadequate ventilation was the most common cause of IAQ problems in 52% of the buildings surveyed (Table 2). Ventilation system problems included insufficient fresh air, poor air distribution, inadequate temperature and humidity control, inadequate HVAC system capacity and inadequate exhaust from occupied areas.

Private sector researchers have shown similar results. Collett et al. (1993), Robertson (1988) and Rask et al. (1990) all found HVAC related inadequacies to be the primary cause of IAQ problems. Collett et al. (1993) observed that inadequate control of the indoor environment by the mechanical ventilation system was the single most frequent cause of occupant complaint in the 85 buildings they investigated. They noted that problems of inadequate outside air supply and poor air distribution within the space may be related to both the design and operational characteristics of the HVAC system. Problems may be a function of the design parameters in buildings with too low of outside air ventilation rates selected to reduce energy costs. Operational deficiencies include building operators closing outside air dampers (for energy efficiency), inappropriate minimum damper settings (particularly in variable air-volume systems), unbalanced air distribution systems and the presence of barriers to effective air distribution, such as partitions, blocking diffusers, furniture or occupants.

Woods et al. (1989) estimated the frequency of occurrence of design and maintenance shortcomings in problem buildings (Table 4). The three most prevalent shortcomings in the problem buildings were inappropriate energy management strategies (90%), inadequate outdoor air (75%) and poor air distribution (65%).

2023687666

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Table 3. Typical types of indoor VOCs and their sources.

Pollutant Types	Example	Indoor Sources
Aliphatic hydrocarbons	Propane, butane, hexane, limonene	Cooking and heating fuels, aerosol propellants, cleaning compounds, refrigerants, lubricants, flavoring agents, perfume base
Halogenated hydrocarbons	Methyl chloroform, methylene chloride, PCBs	Aerosol propellants, fumigants pesticides, refrigerants and degreasing, dewaxing, dry cleaning solvents
Aromatic hydrocarbons	Benzene, toluene, xylenes	Paints, varnishes, glues, enamels lacquers, cleaners
Alcohols	Ethanol, methanol	Window cleaners, paints, thinners, cosmetics, adhesives, human breath
Ketones	Acetone	Lacquers, varnishes, polish removers, adhesives
Aldehydes	Formaldehyde, Nonanal	Fungicides, germicides, disinfectants, artificial and permanent press textiles, paper, particle boards, cosmetics, flavoring agents.

The HVAC system also acts as a pollutant source when it is not maintained properly. Improper maintenance of filters leads to loss of efficiency and reemission of particulate contaminants. Microorganisms breed in various environments present within components of the system and are distributed throughout the building. Studies of indoor air quality of eight offices (Pejtersen et al., 1989 and Fanger et al., 1988), showed that the ventilation system contributed to the pollution of the office building air. Severe pollution sources existed in some of the ventilation systems, ruining the air even before it was supplied to the space.

2023687667

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Other sources of indoor pollutants can come from equipment emissions. If not properly exhausted, gas fired heating equipment may leak CO into the room. Tichenor et al. (1990) found that unvented space heaters had particle emission factors ranging from 1.1 to 5.0 μg/kJ under cyclic operation over a 6 hour period and 0.9 to 8.7 μg/kJ under continuous operation for a 12 hour period. Heaters with radiant/radiant double burners were found to produce over four times as much particulate as heaters with convective/radiant double burners under cyclic operation and almost nine times as much under continuous operation.

Table 4. Design and maintenance shortcomings in problem buildings.

Shortcoming:	% of Buildings
Inappropriate energy management strategies	90
Inadequate outdoor air	75
Poor air distribution	65
Inadequate filtration	55
Contaminated duct linings	45
Inadequate condensate drains	45
Humidifier problems	30

ROOM VENTILATION EFFECTIVENESS

The main purpose of ventilation is to provide fresh air to the occupied zone and to dilute contaminants. The performance of ventilation usually is described using two concepts: air exchange efficiency and contaminant removal effectiveness (Sandberg and Sjoberg, 1983). Ventilation systems are composed of many components and subsystems of components. When evaluating the systems ability to provide fresh air to the occupied zone and to dilute contaminants, it is difficult to assign a single definition since the systems performance is influenced by several factors; therefore, numerous approaches and definitions exist when defining ventilation effectiveness. Most definitions are based on the distribution and mixing of the supply air within the occupied space. Persily (1985) reviewed ventilation effectiveness definitions in mechanically ventilated office buildings. Later, he reevaluated current effectiveness measures (Persily, 1992).

Age of air concepts are a common basis for evaluating ventilation effectiveness (Sandberg, 1983; Fisk, 1983). The age of air in a sample collected at a specific location is the time that has elapsed since

2023687668

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

the air entered the building. The reciprocal of the age of air is a measure of the local ventilation rate. Thus, a relatively low age of air indicates a higher rate of ventilation than a relatively high age of air. Air exchange effectiveness is determined using tracer gas measurements. Common measurement strategies are the step-up, step-down and pulse methods.

The *pulse method* is most sensitive to concentration errors, but measurements must be in short time intervals and it is infrequently used (Sandberg, 1983; Dickson, 1985; Breum, 1988). The *step-up* and *step-down* methods result in smoother concentration changes than the pulse method, which always would present a peak in concentration (Roulet and Cretton, 1992). Other investigators (Niemela et al., 1989; Sutcliffe and Watters, 1990;) suggested that the pulse technique was as reliable as the other two techniques.

The step-up method uses a tracer to mark the fresh air. Using this method, accurate results can be achieved only if the tracer gas can be mixed well with the fresh air and equal tracer gas concentrations at different air supply diffusers can be achieved. If the injection point is located in the zone of low and unstable air movements, notable concentration fluctuations may occur with the step-up technique, which suggests that it is difficult to establish the steady state and relatively long measuring time necessary (Niemela et al., 1989; Sutcliffe and Watters, 1990).

The step-down method is more convenient and useful when good mixing could not be achieved between the tracer gas and the outside air; also when there were many inlets, or when there was too much infiltration, where it would be difficult for the step-up method to achieve equal tracer concentrations in all the inlets and in the cracks. For the step-down technique, however, sometimes the ventilation system had to be stopped and mixing fans used to ensure good mixing. This would disturb the air flow pattern within the room and also the pattern of the age of air (Roulet and Cretton, 1992).

The reasons for uncertainties in measuring ventilation efficiency using tracer gas techniques has been studied by many researchers. Heiselberg (1991) compared the concentration distribution of three contaminants with different densities in full scale experiments at low air change rates. The relative densities of the contaminants to air are high (1.5), neutral (1.0) and low (0.67). Concentration contours with these three contaminants were considerably different. Contours of concentration for the high density case showed clearly that the contaminant was streaming toward the floor region; contours of concentration for the low density case, on the other hand, showed high levels of concentration above the contaminant source. However, when the air change rates increased, the buoyancy effects would decrease and the contaminant distribution would approximate the distribution at high turbulent flow conditions (Heiselberg, 1987; Heiselberg, 1991; Murakami et al., 1983). These measurements were made under isothermal conditions; people and temperature gradients tend to promote mixing.

2023687669

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

The effects of *different tracer gases* on the measurement results have been investigated extensively. Fisk et al. (1983) performed ventilation efficiency measurements using six different tracer gases with a variety of densities. The results of four tracer gases showed very good agreement and the discrepancy from the other two tracer gases was attributed to calibration errors. Niemela et al. (1990) measured ventilation efficiency using three different tracer gases, SF_6, NO_2 and He, with relative densities of 5.10, 1.53 and 0.17, respectively. In cases where tracer gases were injected into the supply air or into the test room with artificial mixing, good agreement among different gases was attained within the limits of experimental errors. These findings are in accordance with the reports of Grimsrud et al. (1980) and Shaw (1984).

Uncertainties of measuring the ventilating efficiency can come from the nonconstant flow rates of the tracer gases, the different time constants of mass spectrometers and the IR analyzers. However these uncertainties usually were considered to be within the range of experimental errors (Grimsrud et al., 1980; Shaw, 1984; Niemela et al., 1990).

The air mixing within the space and the uniformity of the distribution of supply air influence the results of the local age of air. Fisk (1991) pointed out that comparing the value of the local age of air to the nominal time constant of the building does not enable one to distinguish between the effects of mixing and distribution. Fisk (1991) proposed comparing the local age of air to the age of air measured at the return vents. The values of the return age of air throughout the building can be used to evaluate the uniformity of the ventilation air distribution within the building.

Thus to obtain good measurement results, good mixing of the tracer gas in the supply air stream, equal tracer gas concentrations in different inlets and good mixing of the outside air with the return air are essential (Fisk et al., 1988; Roulet and Cretton, 1992). ASHRAE SPC 129 is studying the issue and better guidance is expected.

Two-zone models presented by ASHRAE Standard 62-1989, require that the ventilated space is divided horizontally into two perfectly mixed zones. The ventilation effectiveness in Standard 62 is defined as the amount of the outdoor air from the ventilation system that flows into the occupied zone divided by the amount of outdoor air intake by the ventilation system. ASHRAE 62 fails to define a test procedure for applying the technique. Persily (1992) suggests using a tracer gas procedure described by Janssen (1984).

Contaminant removal efficiency is defined as the ratio of the steady-state concentration of contaminant at the exhaust duct to the steady-state mean concentration in the room (Skaret and Sandberg, 1985; AIVC, 1991). If pollution sources are distributed evenly in the room, contaminant removal efficiency would be similar to the air exchange effectiveness. Contaminant removal efficiency usually is

2023687670

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

evaluated using tracer gas measurements. The removal efficiency defines the ventilation systems ability to remove internally generated contaminants. The efficiency will be location independent if perfect mixing is present. Kim and Homma (1992) used this method in laboratory test rooms to evaluate different ventilation systems. Application of this technique in the field is difficult. Airflows among spaces within the building make single zone calculations difficult. This problem usually is avoided by conducting whole building tests and is only practical for buildings of limited size.

Numerous studies have been performed to evaluate the influence of different factors on ventilation effectiveness. Offermann (1988), Grimitlyn (1982) reported that the relative location of supply air diffusers and air exhaust has a significant influence on ventilation effectiveness. Huvinen et al. (1987), Nguyen (1990), Bauman et al. (1992) and Shaw et al. (1993) studied the influence of partitions and furniture on the ventilation effectiveness in landscaped offices. They reported that this influence is within the accuracy of measurements.

2023687671

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

METHODS - HOW AND WHY SYSTEMS ARE DESIGNED AND THEIR RELATIONSHIP WITH IAQ

HVAC systems are constrained by existing codes and standards, by guidelines reflecting current knowledge, by the state of the art on HVAC designs and by solutions to IAQ problems. HVAC system concept (natural, mechanical ventilation or air conditioning) also depends on the climatic region of the building, the level of the nation's/building owner's concern for energy conservation, IAQ issues and people's welfare. The HVAC system design reflects the objective and subjective judgement of architects and HVAC designers, their preferences as well as the information they can apply.

HVAC systems ranked as the most important construction feature in a survey performed by the Department of Defense, (DOD, 1989) of occupants in new building designs. Two thousand six hundred sixty-four people replied to their questionnaire. They assumed that people like or dislike what they value in a facility and ranked all the features in this manner. They found that people value HVAC systems ahead of all nineteen other features (Figure 2). Forty-nine percent of the returned questionnaires specifically mentioned HVAC and seventy-one percent of those criticized the HVAC system. Therefore, the importance of HVAC systems justifies their priority in design, research and management.

STANDARDS AND GUIDELINES RELATED TO DESIGN

Many codes, standards and guidelines dealing with IAQ exist both nationally and internationally. Through the use of standards and codes, a compromise between energy efficiency and acceptable indoor air quality is attained. These documents specify some minimum requirements for the HVAC system elements and occupant's environmental quality and safety. Codes are intended to serve as minimums only and not as design criteria. They regulate activities which pose a threat to the public health and welfare. Because codes are legally enforceable, they generally contain provisions for noncompliance penalties. Standards and guidelines frequently are issued by national and international standard organizations or by professional organizations and groups of recognized experts. Standards and guidelines may be mandatory or voluntary, but the distinction is not always clear. Standards oten are incorporated into codes either directly or by reference.

Codes

Codes generally are administered on a state or local level. Codes concerning IAQ and HVAC system design are subdivided into two categories: building codes and energy codes. Building codes incorporate IAQ issues into the design process. Portions of building codes which are important to indoor

2023687672

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

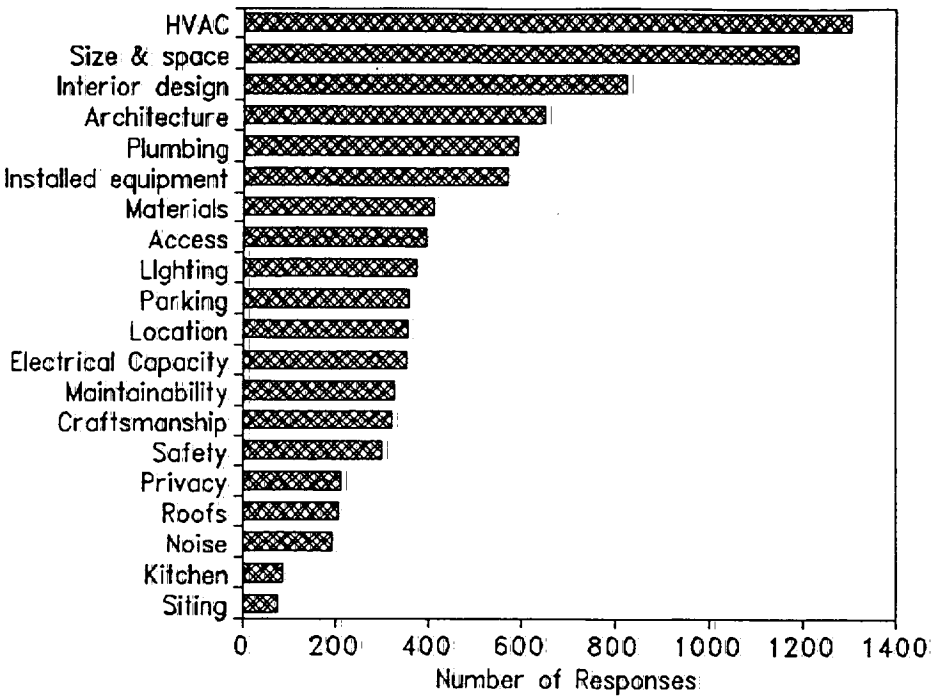


Figure 2. Department of Defense (1989) survey of what features of facilities are valued.

air quality include site preparation, material selection, building envelope design, ventilation design, commissioning and human activity.

The Uniform Building Code (UBC) covers fire, life and structural safety aspects of all buildings and related structures. The publication is sponsored by the International Conference of Building Officials (ICBO). The outline for commercial office buildings is: mechanically operated ventilating systems shall be capable of supplying a minimum of 5 cfm of outside air per occupant with a total circulation of not less than 15 cfm per occupant in all portions of the building during such time that the building is occupied. If the velocity of the air at the register exceeds 10 ft/s, the register shall be placed more than 8 feet above the floor or directly beneath the ceiling. The Uniform Mechanical Code (UMC) contains requirements for the installation and maintenance of heating, ventilating, cooling and refrigeration systems. The publication is sponsored jointly by ICBO and the International Association of Plumbing and Mechanical Officials (IAPMO).

One example where modern building techniques has led to new code requirements concerning

2023687673

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

IAQ is in Canada. Air tight construction techniques that limit infiltration led the National Building Code (NBC) of Canada to make provisions for mechanical ventilation systems in all new self contained dwelling units (Wilson, 1990).

General building designs differ from country to country, (e.g., until recent years the air conditioning of office buildings has not been practiced to any significant extent within the UK). Fire and other regulations in the UK generally discourage the depth of offices with large internal zones, which are common in the USA. Largely due to this, UK codes state that air conditioning systems for the office buildings in the UK may be confined to perimeter areas only (Croom and Roberts, 1981).

Energy codes generally address the issue of energy conservation and have increased in importance since the 1970's. In the past, energy conservation regulation methods have created IAQ problems when IAQ source and control issues are ignored. Consequently, more recent energy conservation standards have addressed and should continue to address, impacts on indoor air quality (Talbott, 1990). The Model Energy Code sets forth minimum requirements for effective use of energy in the design of new buildings and additions to existing buildings. It is based on ASHRAE Standard 90A-1980 and originally was developed jointly by ICBO, BOCA, SBCCI and the National Conference of States on Building Codes and Standards under a contract funded by the United States Department of Energy. The Model Energy Code utilizes standards from many groups such as ASHRAE, ANSI, SMACNA and ARI. The code has been adopted for reference in the UBC. The Model Energy Code calculation procedure covers items such as design requirements, operational characteristics (e.g., temperature, humidity, ventilation, illumination and control modes for occupied and unoccupied hours), mechanical equipment, design capacity, part load profile, building loads and lighting.

Standards and guidelines

Standards and guidelines most relevant to indoor air include: air quality standards, ventilation standards, energy conservation standards and diagnostic protocols. Relevant standard organizing bodies include: ASHRAE, SMACNA, ANSI (American National Standard Institute), ISO (International Standard Organization), NKB (Nordic), DIN (German) and GOSS (Russian) and are listed in Appendix b. National and international standards propose that a successful design considers thermal comfort, energy conservation and IAQ requirements.

Thermal comfort standards

The following national and international standards address thermal comfort issues: ISO 7730, 1993 (International), ASHRAE Standard 55-1992, DIN 1946 Teil 2 (German), Snip 2.04.05.92 (Russian) and others. Both ASHRAE and ISO recently revised their standards for a comfortable thermal

2023687674

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

environment (ASHRAE 55-92, 1993; ISO/DIS 7730, 1993). The foundation for changes incorporated into the standard revisions was based from research performed under environmental conditions similar to commercial and residential buildings with relatively low activity levels (mainly sedentary, 1.2 met), normal indoor clothing (0.5 to 1.0 clo) and a limited range of environmental parameters.

Existing methods for evaluation of the general thermal state of the body for comfort in heat or cold stress, are based on an analysis of the heat balance for the human body. Besides the general thermal state of the body, a person may find the thermal environment unacceptable or intolerable if local influences on the body from asymmetric radiation, air velocities, vertical air temperature differences or contact with hot or cold surfaces are experienced.

ISO 7730 (1993) standardizes the PMV-PPD (predicted mean vote predicted percentage of dissatisfied) index (Fanger, 1972) as the method for evaluation of moderate thermal environments. To quantify the degree of comfort, the PMV-index uses the 7-point ASHRAE thermal sensation scale as follows: +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold. This method also is described in the ASHRAE Handbook of Fundamentals (ASHRAE, 1993). Even if a PMV value of 0 is obtained, there will be at least 5% of the occupants who will be dissatisfied with the thermal environment. The differences and similarities between the two standards are further reviewed in Zhivov and Olesen (1993).

The use of the method is illustrated in Figure 1 of ASHRAE 55-1992, where the optimal operative temperature and the recommended temperature range are shown as a function of clothing and activity. These data are reflected in the ASHRAE Standard 55-92. ASHRAE Standard 55-92 also specifies a range of temperatures where 90% or more occupants find the environment thermally acceptable. For sedentary activity (1.2 met), typical for commercial and residential buildings and typical indoor clothing, the ASHRAE standard recommends the following operative temperature range: winter (heating period, 0.9-1.0 clo) 20°C - 23.5°C, summer (cooling period, 0.5 clo) 23°C - 26°C. Even if the combined influence provides a heat balance for the body as a whole, there may be unacceptable influences on parts of the body from draft, radiant asymmetry or vertical temperature differences.

A draft is probably the most common reason for complaints in air conditioned spaces with occupants at low activity levels (sedentary, standing). The maximum value of mean air speed in the occupied zone depends upon air temperature, t_a and turbulent intensity, Tu. ASHRAE Standard 55-1992 provides information on air speed and temperature limits for light, sedentary and higher levels of human activity; however, precise relationships are not available from this standard. Air speed as high as 1.5 m/s is acceptable if they do not cause problems unrelated to thermal comfort.

2023687675

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

The impact of turbulent intensity on the sensation of the draft has been investigated by Fanger et al. (1988) for different methods of air distribution. The turbulence intensity is derived from the magnitude of the velocity fluctuations in comparison with the mean velocity. Based on the studies of the different air distribution methods, it was found that turbulence intensity in ventilated spaces depends on the type of ventilation system and varies from 10 to 70%. For air velocities ranging from 0.05 to 0.40 m/s and air temperatures from 20 to 26°C, the tests were provided at three levels of the turbulent intensity: low (Tu < 12%), medium (20% < Tu < 35%) and high (Tu > 55%). Periodical fluctuation of air flow is more uncomfortable than nonfluctuating air flow from displacement ventilation systems at the same mean velocity and air temperature.

Both in ASHRAE 55-92 and in ISO 7730 Standard, the limitations for the radiant asymmetry from cold walls is < 10°C and for warm ceilings < 5°C. These data are based on testing with sedentary persons in 0.6 clo clothing (Fanger et al., 1985). Similar data are available for warm walls and cold ceilings. Another comfort parameter, which is described in ASHRAE 55-92 and ISO 7730, is the temperature difference between head and feet. The recommended limit is 3°C. The basis for this value is a study on sedentary persons (Olesen et al., 1979).

New CIBSE guidelines for thermal environment and IAQ are discussed by Appleby (1991). He chaired the multinational task group which has been rewriting Sections A1 and B2, Environmental Criteria for Design, of the CIBSE Guide. This will bring UK comfort and IAQ standards in line with those published by ISO, ASHRAE, DIN and others. The thermal environmental guidelines used by CIBSE are the same as those listed in the recently revised ASHRAE Standard 55-92. Russian Code "Building Norms and Regulations (SNiP) -- Heating Ventilation and Air Conditioning", has a chapter on thermal comfort which is based on numerous studies performed for different levels of human activity in office spaces (Table 5).

HVAC systems become bulky and expensive when they are designed to maintain maximum air velocities and temperature differences in 100% of the occupied zone within the range prescribed by the thermal comfort standards. Taking into consideration the relatively small area of the jet cross section with abnormal parameters, SNiP 2.04.05-92 suggests the following correlations between the maximum air velocity, V_x; the maximum/minimum air temperature, t_x, in the jet entering the occupied zone (or in the reverse flow); the normative values of air speed, V_n; and the temperature, t_n;

$$V_x = N V_n$$

$$t_x = t_n + \Delta t_1 \qquad \text{(heated air supply)}$$

$$t_x = t_n - \Delta t_2 \qquad \text{(chilled air supply)}$$

2023687676

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

where,

N, Δt_1 and Δt_2 are listed in the Tables 6 and 7.

Current diffuser air jet theory makes it possible to predict the maximum air temperature and air velocity at the point of the jet entering the occupied zone. Such an approach to the HVAC system design makes it possible to supply higher air flow rates in ventilated spaces with reduced costs, while maintaining air velocities and temperatures in most of the occupied zone area within a required range.

A comparison of various thermal comfort standards and guidelines is located in Table 8. The ranges of temperatures for summer and winter seasons in most of the standards are similar. SNiP allows a wider temperature range for the cooling mode and a lower temperature during the heating mode. The relative humidity ranges recommended by the three standards are close. Optimal air velocity values in different standards match one another; however, SNiP allows higher velocities during the cooling mode and accepts higher air velocities and temperature deviations in the jet region if there is no work station within the jet area.

IAQ standards and guidelines

The state of the art in ventilation and indoor air quality is outlined and discussed in the following standards: ASHRAE Standard 62-1989, BS 5925:1980 (UK), DIN 1946 Teil 2:1983 (German) and SNiP 2.04.05:92 (Russian). Grimsrud (1990) defines the ideal standard as being constructed from knowledge of the health effects of all pollutants that are found within the building. Once this is known, relative risks of exposure to these pollutants can be determined and acceptable concentration limits can be set. A prescriptive path as well as a performance path can then be recommended.

ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality", is the current ASHRAE guideline for designing for acceptable IAQ. It has been revised from the original IAQ standard, Standard 62-1973 "Standards for Natural and Mechanical Ventilation". This standard specified ventilation rates using two sets of criteria: minimum ventilation rates to accommodate energy conservation [typically 5 cfm (2.5 l/s) per person] and recommended ventilation rates for comfort in odor free environments [typically 15 cfm (7.5 l/s) per person]. No mention was made, however, of the nature of indoor pollutant sources and their impact on indoor air quality.

Two years after publishing Standard 62-1973, ASHRAE published Standard 90-75, "Energy Conservation in New Building Design." Standard 90-75 stated that the minimum column in Standard 62-1973 was to be used for design purposes only, eliminating the established recommended values for ventilation and causing concern that the quality of indoor air would be compromised.

2023687677

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Table 5. Optimal and acceptable thermal comfort parameters in the occupied zone of the office spaces (SNiP 2.04.05-92).

Period	Air temperature, °C		Relative humidity, %		Air Speed, m/s, less than	
	optimal	acceptable	optimal	acceptable	optimal	acceptable
Summer (cooling)	20-22 23-25	less than 3°C higher than the design outside temperature	60-30 60-30	< 65	0.2 0.3	0.5
Winter and intermediate (heating)	20-22	18-22	45-30	< 65	0.2	0.2

Table 6. Coefficient of transition from normative air speed in the occupied zone to the maximum air velocity in the jet.

Comfort conditions	People location	N
Acceptable	Within air jet: - in the core zone - in the main zone Outside the jet In the reverse flow	 1 1.4 1.6 1.4
Optimal	Within air jet: - in the core zone - in the main zone Outside the jet or in the reverse flow	 1 1.2 1.2

Table 7. Acceptable deviation of air temperature in the air jet from the normative air temperature in the occupied zone.

Comfort conditions	Parameter	Acceptable temperature deviation			
		heating mode		cooling mode	
		People location			
		within air jet	outside air jet	within air jet	outside air jet
Acceptable	Δt_1 Δt_2	3 -	3.5 -	- 1.5	- 2
Optimal	Δt_1 Δt_2	1 -	1.5 -	- 1	- 1.5

2023687678

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Table 8. Comparison of various standards/guidelines.

STANDARD	AIR TEMPERATURE °C		RELATIVE HUMIDITY %		AIR SPEED m/s		OUTDOOR AIR m^3/h/person
	optimal	acceptable	optimal	acceptable	optimal	acceptable	
ASHRAE - Summer	24.5	23-26	30-60	30-60	0.2	< 0.2	32
Winter	22	20-23.5	30-60	30-60	0.2	< 0.2	32
DIN - Summer	--	24-27	30-65	30-65	0.2[1]	< 0.25	40-60
Winter	--	22-25	30-65	30-65	0.2[1]	< 0.25	40-60
SNiP - Summer	20-22 23-25	less than 3°C > outside temp	30-60 30-60	< 65	0.2 0.3	< 0.5	20
Winter	20-22	18-22	30-45	< 65	0.2	< 0.2	20

[1]DIN thermal comfort standard for optimal air velocity varies according to room turbulence

ASHRAE Standard 62-1981, "Ventilation for Acceptable Indoor Air Quality," followed, incorporating many major revisions to Standard 62-1973. The standard listed required ventilation rates for nonsmoking and smoking areas rather than minimum and recommended values (although the typical values of 5 and 15 cfm [2.5 and 7.5 l/s] per person were maintained) (SMACNA, 1990a). The 1981 standard also introduced an alternative Air Quality procedure to permit innovative, energy conserving ventilation practices. The alternative procedure allowed the engineer to use whatever amount of outdoor air deemed necessary if it was shown that the levels of indoor air contaminants were held below recommended limits. However, some of the users of Standard 62-1981 found the application of the different ventilation rates for smoking and nonsmoking areas confusing and the recommended maximum concentration of formaldehyde was challenged. For these reasons and in light of rapidly changing technology, ASHRAE authorized an early review of Standard 62-1981 beginning in January 1983 (ASHRAE 62-1989).

Standard 62-1989 retains the two different procedures for ventilation design: the "Air Quality" procedure and the "Ventilation Rate" procedure. The Air Quality procedure is a performance specification that allows acceptable air quality to be achieved within a space by controlling for known and identifiable contaminants. Due to the difficulty in determining source strength, this procedure rarely is used.

2023687679

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

The Ventilation Rate procedure achieves acceptable air quality by specifying a given quantity and quality of outdoor air based upon occupant density and space usage. For general office space, the standard calls for outside airflow rates of 20 cfm/person to provide adequate air quality. The 1989 standard did away with separate ventilation values for smoking and nonsmoking areas, thereby eliminating some confusion.

ASHRAE 62-1989 stresses the point that, no matter which procedure is used, the design criteria and assumptions should be documented and made available to those responsible for the operation and maintenance of the system. It is imperative that the standard be met not only for design purposes but also for when the building is in operation. The goal of this standard is to specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and will avoid adverse health effects. ASHRAE 62-1989 set a guideline for allowable carbon dioxide levels of 1,000 PPM (1.8 g/m^3) and the appendices provide recommendations for other common indoor pollutants based on other sources.

The present scientific basis for the Standard 62 is not strong (Grimsrud, 1990). The two most important gaps in our knowledge base for Standard 62 are health effects related to long term exposure of low levels of pollutants and source emission rates of sources within the buildings. In the absence of this information, the experiences of practicing engineers and designers about "what works" has been used to fill gaps in knowledge. Grimsrud (1990) considered Standard 62 as a transition document that must be updated as new scientific data become available. The prescriptive portion of Standard 62-1989, the Ventilation Rate Procedure, largely ignores source strengths. The only source term considered in determining the ventilation rates of Table 2 of Standard 62-1989 is the CO_2 generation rate of the building occupants. Standard 62-1989 clearly notes that the CO_2 concentration limit is not, in itself a physiological limit. Rather it substitutes for many pollutants associated with occupancy that may cause discomfort in the space. The purpose of Standard 62-1989 is: "To specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to avoid adverse health effects" (ASHRAE 62-1989). Grimsrud (1990) recommended that for the next version of Standard 62, researchers should:

1) define concentration limits following World Health Organization procedures (WHO 1984) and
2) develop a consistent technique for source characterization.

Another approach for regulation of IAQ standards is based on studies conducted by Fanger who used trained people as odor sensors and took them to a large number of buildings in Denmark (Appleby, 1991). To utilize this method, Fanger developed new units for describing odor: the olf and the dicipol. This approach accounts for human and nonhuman sources of pollution and is listed in the CIBSE Guide for determining outdoor air requirements.

2023687680

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Reviewing the new CIBSE guidelines on IAQ, Appleby (1991) states that buildings should be designed with odor emissions from building related sources, such as furniture, carpets and environmental systems, at no more than 0.1 olf/m^2. Therefore, close attention should be paid to the specification of low emission materials cleaning products, maintenance materials and equipment. Outdoor air quality may be below 0.1 decipol in rural areas and may exceed 0.5 decipol in towns. Ventilation effectiveness, E_v, is 1.0 when the air diffusion system creates perfect mixing. When there is some short circuiting, E_v can be 0.9 and below. For systems with air supply into the occupied zone and supply air temperature is below room air temperature, E_v may be 1.4 or even higher.

Based on analyses of the current CIBSE and ASHRAE recommendations of outdoor air supply rates and data obtained by Fanger, Awbi (1991b) has shown differences for office buildings using a subjective assessment procedure. The differences were due to the pollution from building materials, furnishing and the ventilation system, which were more significant than those from occupants in office buildings. This pollution has not been accounted for in these standards. The amounts of outdoor air per person prescribed by different standards and guidelines are listed in Table 8.

Levels of outdoor and indoor air quality are listed in Tables 9 and 10. These tables are from "Guidelines for Ventilation Requirements in Buildings", Commission of the European Communities (1992). The decision on the desired level of air quality in a space, according to the Guidelines, depends mainly on economic considerations and on the application of the space.

In 1987, the Nordic Committee on Building Regulations set up an indoor climate committee to provide support for the joint Nordic activity in this area. International experts from Denmark, Finland, Iceland, Norway and Sweden served on this committee to develop common recommendations. In 1991, the Board of the Indoor Climate Committee of the Nordic Committee on Building regulations approved the NKB Publication No 61E on "Indoor Climate - Air Quality". The following are the highlights of these requirements for buildings and ventilation systems listed in this document:

> Since ground and building materials can be a source of indoor air pollution, the choice of building construction shall be made with regard to the nature of the ground so that problems connected with indoor climate do not arise. Particular account shall be taken of dampness and radon.
>
> To secure a satisfactory indoor environment, a building shall be placed in as pure an outdoor environment as possible. The ventilation system shall be planned so the risk of spreading pollution in the building is kept low.
>
> Building materials and finished surfaces shall have the lowest possible emission properties. Fittings, fixtures, furnishings and furniture are often just as significant a source of pollution as are

2023687681

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

building materials.

Buildings shall be designed so that it is possible to clean surfaces in contact with supply air or room air. Such surfaces shall be cleaned before the building is taken into use. Surfaces which are likely to become heavily soiled shall be readily accessible and easily cleanable.

Table 9. Outdoor levels of air quality (CEC, 1992).

	Perceived air quality, decipol	Air pollutants			
		CO_2 mg/m_3	CO mg/m_3	NO_2 mg/m_3	SO_2 mg/m^3
At sea	0	680	0-0.2	2	1
In towns, good air quality	< 0.1	700	1-2	5-20	5-20
In towns, poor air quality	> 0.5	700-800	4-6	50-80	50-100

Table 10. Three levels of perceived indoor air quality (CEC, 1992).

Quality level (category)	Perceived air quality		Required ventilation rate, l/s
	% dissatisfied	decipol	
A	10	0.6	16
B	20	1.4	7
C	30	2.5	4

The requirements for outdoor air flow rates are based on data received by Fanger et al. (1988) and are similar to those from the "Guidelines for Ventilation Requirements in Buildings" (ASHRAE Handbook, 1992). Outdoor air intakes are recommended to be placed where the air is cleanest and has the lowest temperature in the summer. Consideration should be given to the position of the building, the chimneys and other sources of pollution. Where it is required because the quality of outdoor air is unsatisfactory, the supply air shall be filtered to remove dust, pollen and other particulate pollutants.

As a protection against malfunction of the ventilation system, every habitable room shall be provided with an operable window for ventilation. Referring to different studies conducted by Jaakkola et al., (1989), individual controls of room temperature increases satisfaction and reduces sick building symptoms. Based on that, they recommend locating control devices so they are easy to reach, understand and operate.

2023687682

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

The design of air conditioning and ventilation systems for office buildings in Russia is regulated by Building Norms and Regulations "Commercial Buildings and Constructions" (SNiP 2.08.02 - 89). According to this document, commercial buildings should be equipped with ventilation or air conditioning systems to provide optimal or acceptable thermal comfort in the rooms. The amount of the outdoor air to be supplied for each person in the office space should be 20 m^3/h. The amount of the supplied air should be based on the assimilation of the excessive heat, moisture and CO_2. The reference emissions of contaminants by the occupants are listed in Table 11.

Table 11. Emission of heat, moisture and CO_2 by one person in the office space.

Air temperature in the occupied zone, °C	Heat release, W			Moisture release, gr/h	CO_2 release, l/h
	Total	Sensible	Latent		
20-22	105	70	35	50	20
23-25	111	60	51	75	20
26-28	116	49	67	100	20

Due to the climate and energy conservation concern, most of the office buildings in Russia are equipped with ventilation systems with air handling units containing spray chambers for adiabatic cooling. In winter, heating is provided by hot water heating systems and/or warm air heating combined with the ventilation system. To reduce infiltration during heating periods, the "Designer's Manual" recommends that the amount of supplied air exceed the amount of exhausted air from the ventilated office room by 1 ach, but by less than 6 m^3/h per m^2 of the room area. It is recommended that the air supply be delivered directly into the ventilated space. However, 50% of the total amount can be supplied into the adjacent room or into the corridors. It is recommended that air be supplied into the upper zone of office spaces through regulated air diffusers.

Typically, information about health effects is used to set limits on the concentrations of pollutants found within buildings (Grimsrud, 1990). Organizations such as NIOSH, ACGIH, WHO, EPA and OSHA have set limits on concentration levels for various substances observed in indoor air environments. There can be significant differences between these standards based on whether they are set to protect the occupational work force or whether they are for the general public.

Concerning IAQ standards for the future, Grimsrud (1990) suggests that these standards should merge the approach adopted by Standard 62 with the approach provided by Ole Fanger and his colleagues. Fanger's approach uses a consistent set of units for source strength, pollutant concentration and has projected a concentration limit for acceptable air quality based upon experience in Danish office buildings. While there are problems with this approach because of its reliance on odor sensation as the

2023687683

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

fundamental pollutant detector, it has a logical consistency and simplicity that is appealing.

Energy standards and guidelines

Talbott (1990) believes many parallels exist in the development of energy conservation standards and IAQ standards i.e., simple prescriptive methods have evolved into performance methods and simple performance methods could evolve into more comprehensive computer modeling applications. IAQ issues have occurred in energy conservation standards and vice versa; however, the question still remains as to whether current standards effectively address IAQ concerns.

ASHRAE 90.1-1989 is a design standard for energy efficiency. The Standard is the basis of energy codes adopted in over 40 states in the USA as well as for energy codes developed by at least seven other countries. By October 1994, each state must certify that its commercial building energy code provisions meet or exceed the requirements of ASHRAE 90.1-1989, in accordance with the Energy Policy Act of 1992.

HVAC SYSTEM DESIGNS

Increasing emphasis on both IAQ in office buildings and energy conservation makes it imperative that the outdoor air is distributed properly within the interior space efficiently and cost effectively. Among the objective constraints architects and designers have are the space available for the HVAC system and its location, the weight of equipment and the kind of structural supports, acceptable noise levels and whether the architect wants to have the system visible and/or even emphasize its elements by different colors or (more commonly) hide it. Choosing the type of HVAC system and its elements, the designer also should consider the reliability and controllability as well as the initial and operating costs.

In the initial phases of building design, the engineer seldom has sufficient information to evaluate the design (ASHRAE Handbook, 1992). Therefore, most experienced engineers have developed rules of thumb to estimate the building space needed. The air conditioning system selected, the building configuration and other variables govern the space required for the mechanical system. The final design is usually a compromise between what the engineer recommends and what the architect can accommodate.

General types of air conditioning systems

Air Conditioning systems for office buildings can be classified as:

1) central,

2023687684

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

2) local or

3) central combined with local systems of radiant heating/cooling or local humidification.

Central Ventilation Systems provide complete sensible and latent cooling, preheating, heating and reheat and humidification of the air supplied by the system. Heating may be accomplished by the same airstream, either in the central air conditioning system or at a particular zone. The term zone implies the provision or the need for separate thermostatic control, while the term room implies a partitioned area that may or may not require separate control. To avoid biological pollution sources, air conditioners and terminal units which cool the air should be easily accessible so that bacteria and fungi that settle and multiply in the condensate pans can be cleaned periodically. Central systems can be classified in two basic categories (ASHRAE Handbook, 1992; Designers guide, 1992):

1) single duct systems and

2) dual duct systems.

Single duct systems contain the main heating and cooling coils in a series flow air path; a common duct distribution system at a common air temperature feeds all terminal apparatus. Dual duct systems contain the main heating and cooling coils in parallel flow or series parallel flow air paths with either (1) a separate cold and warm air duct distribution system that blends the air at the terminal apparatus or (2) a separate supply air duct to each zone with the supply air blended to the required temperature at the main unit mixing dampers.

The single and dual duct systems for central systems may be subdivided further into the following classes:

1) constant air volume,

2) variable air volume,

3) single zone or

4) multizone.

By maintaining constant airflow, constant air volume systems change the supply air temperature in response to the space load. A variable air volume system controls temperature within a space by varying the quantity of constant temperature supply air into the space. Rarely is the supply air temperature changed. The greatest energy savings associated with VAV systems occur at the perimeter zones, where variations in solar load and outside temperature permit reduction in supply air quantities. However, they become cost efficient when the maximum air flow rate can be decreased throughout a year by at least 10% (Zhivov, 1990).

Single zone air systems supply air into a single temperature control zone and respond completely to the space needs. Many adaptations have been implemented, but the basic multizone air system supplies

2023687685

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

air into several zones of unequal load from one centrally located air handling unit. The different load requirements are met by mixing cold deck, hot deck and warm (bypassed) air through zone dampers in the air handling unit. With multizone air systems there are relatively constant heat loads and pollution transmission across the interior spaces. When needed, they can be divided into further zones to provide more uniform temperatures and pollution control. Heating and cooling loads within exterior zones are more affected by varying weather conditions, wind, building orientation, temperature and geographical location. Down drafts at window locations and radiation effects from cold glass surfaces can create discomfort for sedentary occupants.

The central air conditioning system can contain an air handling unit with an outside air intake, mixing plenum(s), filter section, preheat coils, cooling coils, heating coils, bypass section(s), humidifiers, reheat coils, automatic dampers, system sensors and automatic control, supply air diffusers, return air intakes, return air ducts, return air fan, exhaust fans and air exhaust. To protect the system from being polluted by particulates in outdoor air, air filters should be placed at the intake and a second air filter of better quality should be placed on the supply side of the air handling unit downstream of the fan or any aerosol producing device. Further necessary filters, e.g. HEPA filters, should be installed close to the room. There should be an adequate seal between the air filters and the walls of the surrounding ducts or units. All filters should be protected from water due to spray washers, cooling coils, snow, rain etc. It should be possible to assess the condition of the filter at any time (e.g., its pressure drop, contamination level).

As stated in the 1992 ASHRAE Handbook, central air conditioning systems have the following advantages and disadvantages;

Advantages

1) The central mechanical equipment room location for major equipment allows operation and maintenance to be performed in unoccupied areas and permits the maximum range of choices of filtration equipment, vibration and noise control and the selection of high quality and durable equipment.
2) Complete absence within the conditioned area of piping, electrical equipment, wiring, filters and vibration and noise producing equipment reduces potential harm to occupants, furnishings and processes minimizing service needs.
3) Central systems have the greatest potential for the use of outside air and "free" cooling systems instead of mechanical refrigeration for cooling.
4) Seasonal changeover is simple and readily adaptable to automatic control.
5) Gives a wide choice of zoning, flexibility and humidity control under all operating conditions, with the availability of simultaneous heating and cooling, even during off season periods.
6) Air to air and other heat recovery systems may be readily incorporated.

2023687686

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

7) Permits good design flexibility for optimum air distribution, draft control and adaptability to varying local requirements.

8) Well suited to applications requiring unusual exhaust or makeup air quantities (negative or positive pressurization, etc.).

9) Adapts well to winter humidification.

10) The primary system can be used to introduce outside air required for ventilation without the need for supplemental systems.

11) By increasing the air change rate, these systems are able to maintain the closest operating condition of ± 0.15 °C dry bulb and ± 0.5 % relative humidity relatively simply; today there are systems that essentially maintain constant space conditions.

Disadvantages

1) Central air conditioning systems require additional duct clearance, which reduces usable floor space and increases the height of the building.

2) Depending on layout, vertical shaft space is needed for distribution requiring larger floor plates.

3) The accessibility of terminal devices requires close cooperation between architectural, mechanical and structural designers, as well as the occupant.

4) Air balancing, particularly on large systems, can be more difficult.

5) Perimeter heating systems are not always available for use in providing temporary heat during construction.

Air distribution systems within rooms

Air diffusers distribute the supply air within a ventilated space. The amount of supply air provided depends upon the thermal comfort and the air pollution control desired within the occupied space and the proper selection of the air distribution system. The systems are classified as:

1) mixing type,

2) displacement and

3) local.

In mixing type systems, conditioned air is normally supplied to air outlets at velocities much greater than those acceptable in the occupied zone. Conditioned air temperature may be above, below, or equal to the air temperature in the occupied zone, depending on the heating/cooling load. The diffuser jets mix with the ambient room air by entrainment, which reduces the air velocity and equalizes the air temperature. The occupied zone is either ventilated by the decaying air jet directly or by the reverse flow created by the jets. Mixing air distribution creates relatively uniform air velocity, temperature, humidity and air quality conditions in the occupied region.

2023687687

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

In the mixing type systems, air can be supplied by compact incomplete radial, radial, conical or linear jets. The most common air diffusers used in office buildings are as follows:

1) round ceiling mounted air diffusers supplying radial or conical jets attached to the ceiling,
2) rectangular ceiling mounted air diffusers supplying two, three or four way incomplete radial air jets,
3) ceiling mounted linear air diffusers supplying linear jets through one or two jets through the slots,
4) ceiling mounted perforated panels supplying downward projected jets,
5) side wall mounted grills supplying incomplete radial jets attached to the ceiling,
6) side wall slot type air diffusers supplying linear air jets attached to the ceiling and
7) side wall mounted nozzles supplying compact air jets.

Ceiling mounted round and linear air diffusers can supply either straight flow or swirling jets. For variable air volume systems, the reduction of supply air flow reduces the air velocity at the outlet. This decreases the throw and may cause a cold air draft in the occupied zone and poorly ventilated stagnant zone. Specially designed air diffusers may be necessary, (Zhivov, 1990), when the reduction of air flow exceeds 40% of the maximum load. Special air diffusers for variable air volume office systems can be classified as follows:

1) jet assisted air diffusers,
2) air diffusers with regulated supply area,
3) air diffusers with air to air induction boxes and
4) air diffusers with fan assisted induction boxes.

Displacement ventilation systems supply conditioned air at a temperature slightly lower than the desired room air temperature in the occupied zone. The air is supplied from air diffusers at low air velocities (0.5 m/s or less). The diffusers are shaped as cylinders, half/quarter cylinders or flat panels and are located at or near the floor level. The supply air is introduced directly to the occupied zone. The return air diffusers are located at or close to the ceiling where the warm room air is exhausted from the room. The supply air is spread over the floor and then rises as it is heated by the heat sources in the occupied zone. Heat sources in the occupied zone create upward convective flows in the form of thermal plumes; these remove heat and contaminants which are less dense than air from the occupied zone.

The air volume in the plumes increases as they rise because the plume entrains ambient air. A stratification level exists where the airflow rate in the plumes equals the supply airflow rate. Two distinct zones are thus formed within the room, one lower zone below the stratification level with no recirculation flow and one upper zone with recirculation flow. The height of the lower zone depends on the supply air flow rate and characteristics of heat sources and their distribution across the floor area. In a properly designed displacement ventilation system, the height of the lower zone is above the occupied zone so the

2023687688

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

occupied zone can be ventilated effectively. For this type of system to function properly, a stable, vertically stratified temperature field is essential.

The comparison of conventional mixing and displacement systems for US office buildings is provided by Seppanen et al. (1989) for four representative US climates. Energy consumption, air quality, thermal satisfaction and the cost of the systems were calculated with the DOE-2.1 building simulation program using the results from recent laboratory measurements. They concluded;

1) Displacement ventilation systems create better average air quality in the occupied zone than traditional mixing VAV systems with recirculation.
2) Displacement ventilation systems do not have much influence on energy consumption; however, their first cost is significantly higher than VAV systems because cooling panels usually are required (recommended when the cooling load exceed 40 W/m^2).
3) Displacement ventilation creates a better thermal environment than mixing systems.

Mixing type air distribution with linear ceiling mounted air diffusers and displacement ventilation also were tested and compared by Holmberg et al. (1987) for the three cooling modes: 45 W/m^2(summer mode), 25 W/m^2 (autumn/spring mode) and 4 W/m^2 (winter mode). The researchers reported good comfort (in accordance with the ISO 7730 standard maintained under specified circumstances) with both air distribution methods in winter and spring/autumn modes. However, in the summer case, the ISO 7730 standard dictated the cooling power supplied to the room. Air jets through the ceiling mounted air diffusers could supply a maximum air cooling power of about 45 W/m^2, with a temperature difference of 10°C between supply and exhaust air temperatures and not cause overly high velocities. In contrast, the displacement ventilation method puts a limitation on a temperature difference and requires, consequently, a higher airflow to supply equally high cooling power without causing an extensively high vertical temperature gradient in the room. With low velocity air supply devices, the difference between the supply and exhaust air temperatures has to be kept below 7°C (3-5° according to other sources).

The air quality was good with both air distribution methods in the summer and spring/autumn cases, due to the high air flows of 5.7 and 3.8 l/s per $1m^2$. In winter with the air flow of 0.67 l/s per 1 m^2 the differences in air age and air exchange efficiency were too small to ascribe better air quality to the displacement ventilation. The simulation of passive smoking at the work place showed that convective currents around a seated person have the ability to attract smoke, resulting in very high concentrations in the breathing zone when a displacement ventilation method was used. A higher concentration in the breathing zone also occurred in winter compared to summer for mixing type systems.

Local ventilation systems for office spaces were introduced during the last few years. Desk top local supply brings ventilated air closer to the breathing zone and thus decreases the mixing of fresh outdoor air with ambient air. These systems also allow occupants to fine tune the direction of the air jet

2023687689

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

and the amount of air supplied to create the proper microclimates. Desk top systems may have different designs (Atlas Compac, 1989; Johnson Controls, 1988;). Several studies were conducted (Faulkner et al., 1993; Bauman, 1993 and Croom, 1988) to evaluate thermal comfort and indoor air quality provided with these systems.

Faulkner et al. (1993) and Bauman et al. (1993) conducted their studies in a furnished experimental facility with three work stations. Air supply per work station varied from 29 to 83 cfm. Two sizes of air supply nozzles were used: the standard size provided by the manufacturers and a larger one. The desk top system can provide thermal comfort in the occupied zone (0.1 to 1.1 m heights) for a wide range of heat loads. To reduce air velocities at large air flows, the researchers directed air jets along the walls and/or used larger supply nozzles.

In the tests with nozzles pointed towards occupants and with 100% outside air supplied at the rate of 83 cfm per work station, the age of air was approximately 30% less than the age of air that would occur throughout the test space with perfectly mixed outdoor air. With smaller air supply rates and/or air supplied parallel to the edges of the desk, ages of air were not significantly lower than the age with perfect mixing. However, the amount of outdoor air supplied directly toward the breathing zone can be reduced to compare with mixing type systems. It is also worthwhile to test the air quality on the work station with a reduced amount of outdoor air (provided there is low mixing with ambient air which allows higher concentrations and deviation from the thermal comfort parameters outside the work station). The authors acknowledge the potential to significantly reduce the amount of energy used by the task conditioning system.

Arens et al. (1990) came up with an interesting finding by experimenting with desk top systems. They concluded that the existing thermal comfort standards might not be compatible with such systems due to the higher thermal stratification exceeding 3°C produced when using them at work stations. This suggests a more pragmatic and flexible approach should be adopted in evaluating comfort with local comfort systems. Effective support for such an approach comes from Schiller et al. (1988) and Croom (1988).

Comparing the air supply to individual occupants with the mixing type air distribution, Appleby (1988) concludes that the local air supply has significant advantages in providing high ventilation efficiency, but allows lower primary air temperature difference. He sees in this system a potential for further improvements in efficiency and running costs. He states that further work is required in order to investigate the operation and performance of this system in the field. There is no absolute universally applicable method. Every method has its advantages when applied to the appropriate situation: the various methods are complementary to each others.

2023687690

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Duct systems

NFPA Standard 90A states that ducts for commercial buildings must be iron, steel, aluminum, concrete, masonry or clay tile. Materials, like fiber glass, when not used as vertical risers serving more than two stories or in systems with air temperatures higher than 121°C, also may be used. Metal, rectangular, round and flat oval ducts are used to connect mixing boxes, diffusers and other terminals. Flexible ducts are used to connect the air distribution system. To avoid pollution sources and dust accumulation, the inner surfaces of ducts for supply and recirculated air should be smooth and resistant to abrasion. Provisions should be made for inspection and efficient cleaning of the ducts. Installations unrelated to the ventilation system should not be installed in the ducts.

COMMISSIONING & TROUBLESHOOTING IAQ PROBLEMS

The magnitude of indoor air quality (IAQ) problems in existing buildings has been identified and quantified in a number of studies (Steelcase, 1991; Crandell, 1987; Kirkbride et al., 1990). Poor IAQ has been perceived as a serious hazard by building occupants, owners and managers throughout the world (Steelcase, 1991). Comfortable heating and air conditioning has been perceived to be very important by a substantial majority of building occupants, managers and owners; however, a majority of them feel that comfortable conditions are not being provided.

A properly designed, well constructed, properly functioning and well maintained HVAC system will reduce, if not eliminate, the majority of IAQ complaints by building occupants (Sterling et al., 1993). One of the main processes by which this can be achieved is through proper building commissioning. This section discusses the methods normally followed in building commissioning. Troubleshooting IAQ problems in office buildings also is discussed.

What is commissioning?

Commissioning can be defined as the process of achieving, verifying and documenting a concept through design, construction and a minimum of one year of operation (ASHRAE Handbook, 1989). Commissioning of a HVAC system is not simply starting it up after construction and making sure that the equipment is in working order, but it is a process of system delivery that begins when a project is conceived and ends when the useful life of the resulting structure is complete (Sterling et al., 1992).

Commissioning building mechanical systems has been a topic of interest to ASHRAE since at least 1984, when a forum on building commissioning was conducted at the ASHRAE Annual Meeting in Kansas City (Elovitz, 1992). ASHRAE also established a special committee to prepare guidelines on commissioning building HVAC systems. That committee produced the ASHRAE 1989 Guideline for

2023687691

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Commissioning. The ASHRAE Guideline establishes procedures for the HVAC commissioning process for each phase of the project: program, design, construction, acceptance and post acceptance. The Guideline is intended to assist professionals by providing procedures and methods for documenting and verifying the performance of HVAC systems so they operate in conformity with the design intent. The Guideline presents a format for documenting the occupancy requirements, design assumptions and the design intent for the HVAC system. A fully functioning, fine tuned HVAC system with complete documentation would be the end result of the commissioning process.

The original ASHRAE Guideline for Commissioning did not focus on IAQ control. A committee is now revising the guideline and will include recommendations on how to avoid IAQ problems in new buildings (Sterling et al., 1993). Sterling et al. (1993) developed and proposed a checklist as a guide to be used during the commissioning process to verify that IAQ requirements have been addressed by the design and construction teams.

The need for commissioning

The need for proper commissioning of HVAC systems is apparent when one considers that many properly designed and installed systems have failed to produce their intended functional performance (Brickman, 1989). For example, a recent investigation of 51 school buildings in Ontario illustrated the typical problems found in buildings that received no commissioning (Khandekar and Tamblyn, 1990). The problems associated with a lack of commissioning included: unreliable system operation, indoor air quality problems and higher operation and maintenance costs (Tamblyn, 1992).

The benefits of proper HVAC system commissioning are: (a) a system that operates according to design intent, (b) proper documentation and system operation, (c) operating personnel who understand the system and know how to operate it, and (d) operating and maintenance cost savings. Sterling et al. (1992) noted that commissioning could eliminate as much as one half of all IAQ related complaints. In addition, ongoing performance auditing of building after occupancy could virtually eliminate IAQ and comfort complaints in new and renovated buildings to which the commissioning process has been applied.

The commissioning process

Many different approaches to commissioning have been developed. In the traditional process, the consultants define the environmental control and building components (Sterling, 1989). After construction and system installation, inspectors and contractors evaluate the effectiveness of environmental control systems through fairly narrow guidelines (e.g., air balancing tests and tests of the functional performance of control systems and equipment). The building inspectors and contractors then report back to the engineer, who report back to the architect. The architect then certifies the building as substantially

2023687692

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

complete, when all inspections and approvals have been given.

Trueman (1989) has developed and applied an approach that consists of three parties: (a) the contractor plans and carries out the physical activities of the commissioning process, (b) the consulting engineer specifies what the contractor will be responsible for and verifies acceptable performance in all respects, and (c) the owner defines his expectations with respect to commissioning, which, will define the responsibilities of the consulting engineer and contractor.

In some cases, commissioning of HVAC systems is ignored or left to people who do not fully understand the design criteria or intended operation of the system (Brickman, 1989). When commissioning is done by technicians who do not understand the system, the design is compromised. To this end, Brickman (1989) recommended that the commissioning specification must start with the qualifications of the "commissioning authority", the person to be charged with the responsibility of directing the commissioning process. The commissioning authority may be the design professional or the installing contractor or a third party specifically engaged for the commissioning process, but this person must be capable of fully understanding the design criteria and the systems' description and operating modes.

Most building owners and designers recognize that commissioning of building systems is desirable. However, building owners will not invest in commissioning without a better understanding of the benefits. HVAC practitioners will have to develop and deliver a commissioning process that can address the following issues: design intent, building occupancy and use and building operation and maintenance (Tamblyn, 1992). Building owners must be educated to apply the process to achieve long term benefits.

A great deal of confusion exists concerning the shared responsibility among the several parties involved (Lawson, 1989): (a) the contractor, who is responsible for putting the system into operation, (b) the engineering consultant, who is responsible for verifying that the contractor has executed the work substantially in accordance with the consultant's documents and (c) the owner, who believes the contractor and consultant are paid for a complete job and questions why pay more for commissioning.

Lawson (1989) has also outlined problems that have been observed in the commissioning process. These included: (a) poorly planned approach for initial startup of the mechanical system, (b) startup technicians who do not understand the proper method of system startup and are not properly trained in this type of work, (c) lack of involvement in commissioning process by the design engineer and mechanical project manager, (d) incomplete startup process of mechanical system, (e) poor documentation, (f) improperly planned owner and personnel training, (g) lack of personnel participation in training and (h) poor communications among all parties.

2023687693

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Troubleshooting IAQ problems

The process of solving IAQ problems that result in comfort and health complaints can be a slow one, involving several trial solutions before successful remedial actions are identified. Frequently, IAQ problems in office buildings cannot be identified or remedied without a comprehensive building investigation. IAQ investigations are conducted upon request from employee groups, unions, management and local, state and federal agencies. Generally, these requests are in response to existing worker health complaints and illness.

IAQ investigations usually are first carried out through self evaluation. If further evaluation is needed to resolve the problem or if technical expertise is needed to complete any of the investigation, professional assistance usually is sought because most firms lack the necessary technical skills to adequately evaluate, diagnose and treat IAQ problems. On site assistance usually is provided by any of the following sources: (a) local or state health departments or consulting programs, (b) private consultants (Industrial hygiene consultants, usually members of the American Industrial Hygiene Association and engineering consultants sometimes certified by the National Environmental Balancing Bureau) and (c) NIOSH - Health Hazard Evaluation Program.

Approaches to IAQ investigation

Thousands of buildings have been investigated throughout North America and Western Europe (Collett and Ross, 1993). The evaluative strategies and protocols used by various investigators have been described in the scientific literature, including those used by government agencies (NIOSH, 1989; EPA, 1991), private consultants (Sterling et al., 1987; Lane et al., 1989; Yocom and McCarthy, 1991), research scientists (Goyer and Nguyen, 1989; Gammage et al., 1989) and medical doctors (Quinlan et al., 1989). Review of these strategies shows a general consistency and commonality in approach (Collet et al., 1993). Most of the published protocols recognize the need to employ a multidisciplinary approach to the evaluation of IAQ problems, an approach that views buildings as complex, dynamic systems.

The building owners or office managers in requesting help from an IAQ consultant to solve IAQ problems invariably ask for air sampling to determine what is in the air that could cause the problem (Yocom and McCarthy, 1991). However, the problem usually is approached in a series of sequential phases with the simplest and most cost effective tasks performed first (Yocom and McCarthy, 1991; EPA, 1991). Collection of samples requiring sophisticated and expensive analysis is done only if indicated by the results of the earlier phases.

The IAQ investigation is a series of information gathering, hypothesis formation and hypothesis testing (EPA, 1991). The objectives are to: (a) determine whether an IAQ problem exists, (b) identify the

2023687694

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

cause of the problem, (c) design and implement modifications to alleviate the problem and (d) reevaluate conditions after modifications have been implemented to test the effectiveness of the design solutions (Collett et al., 1993). Unfortunately, reevaluation rarely is done due to costs.

Gorman and Wallingford (1989) discussed the NIOSH guide for IAQ investigations based on their experience in conducting about 450 field investigations of IAQ problems in many types of buildings. The NIOSH investigation teams typically include an industrial hygienist and a physician or nonphysician epidemiologist, although other professionals (such as an engineer) have been included. Most investigations include a background assessment, an initial site visit and followup visits, if necessary. Background assessment is conducted to obtain as much historical information as practical on the building itself and to establish a chronology of the problems. The initial site visit includes a walk through evaluation, personal interviews and onsite environmental monitoring. If during the background assessment or the initial site visit a problem has been identified that needs further definition, or if no problem can be isolated, an additional site assessment is performed. This can involve more specific and extensive environmental monitoring for chemical and/or microbiological contaminants and/or tracer gas monitoring to evaluate the ventilation system.

Woods et al. (1989) described phases in the diagnosis of buildings experiencing IAQ problems as (1) consultation, (2) qualitative diagnostics and (3) quantitative diagnostics. By performing diagnoses in this staged manner, it is possible to prevent and resolve many problems without resorting to time and resource consuming data acquisition unless absolutely necessary (Woods et al., 1989).

Yocom and McCarthy (1991) developed a protocol in the conduct of SBS studies. The protocol includes: (1) an initial survey including, discussion of the nature of the problem with building owners/operators, building engineers and mechanical maintenance personnel, discussion of symptoms with complainants, and initial measurement survey; (2) detailed questionnaire for building occupants to determine if source of complaints can be correlated with a specific variable; (3) more detailed site survey involving measurement of air exchange rates, IAQ and thermal comfort parameters; (4) data analysis; (5) recommend remediation measures and (6) repeat application portions of surveys under items 1, 2 and 3 to determine the effect of remediation measures on reductions in air contaminant concentrations and in the extent of complaints among building occupants.

Collett et al. (1993) developed an approach consisting of the following stages: (a) initial assessment, (b) assessment of health and comfort concerns, (c) IAQ and thermal comfort monitoring, (d) follow up IAQ measurements, (e) ventilation measurements, (f) development and implementation of mitigation strategies and (g) post implementation assessment.

2023687695

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

OPERATION AND MAINTENANCE

Typically, IAQ is addressed only after it becomes a reported problem. However, prior to becoming an occupant complaint, the IAQ must have been a problem as well. Do IAQ guidelines and standards need to be developed for system maintenance and operation?

Traditionally, HVAC O&M activities center around maintaining building occupant comfort in terms of temperature and humidity. Current, O&M procedures for IAQ are not significantly different, but include a focus on aspects of existing procedures that impact occupant comfort as related to IAQ. Case studies of O&M related IAQ problems have not shown that new activities are needed, but that problems arise when well known, accepted procedures are not followed (Siliwinski et al., 1991).

Many office buildings have preventive maintenance schedules either on paper or as computerized systems. As part of the IAQ management plan, the specific IAQ O&M activities should be integrated into existing preventive maintenance scheduling, or managed as an element of an IAQ database.

O&M activities can be focused on a component level, from the perspective of indoor air quality impact. Within the IAQ plan these activities are implemented either on a routine basis, or in special cases such as the acceptance of a new building, installation of new furnishings in an existing building, or after storm or fire damage.

Routine O&M procedures for IAQ concentrate on proper operation and maintenance of building HVAC system components and control of indoor air contaminant sources. Specific components identified as having IAQ impacts by Siliwinski et al. (1991) are as follows:

1) ventilation rates,
2) decentralized coils,
3) central filters,
4) other air cleaners,
5) economizer systems,
6) evaporative condensers,
7) pesticide control,
8) plumbing systems,
9) refrigeration equipment,
10) humidifiers,
11) decentralized filters,
12) electronic air cleaners,
13) insulation,
14) cooling towers,

2023687696

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

15) air to air heat exchangers,
16) sumps,
17) lighting systems and
18) exhaust hoods.

There may be several conditions under which special O&M procedures should be followed to ensure maintenance of acceptable IAQ. These include commissioning of new buildings; after extensive retrofit and refurnishing; after building structural damage due to storm, fire, or other cause; and as part of mitigating certain IAQ problems such as asbestos.

Developing an IAQ management plan

EPA (1991) outlined a procedure to develop a management plan. IAQ management will be best facilitated if one individual is given overall responsibility for IAQ. EPA's suggested IAQ manager's ongoing responsibilities include the following:

1) developing an IAQ profile,
2) overseeing the adoption of new procedures,
3) establishing a system for communicating with occupants about IAQ issues,
4) coordinating staff efforts that affect indoor air quality and making sure that staff have the information and authority to carry out their responsibilities,
5) reviewing all major projects in the building that could create IAQ problems,
6) periodically inspecting the building for indicators of IAQ problems,
7) managing IAQ related records,
8) responding to complaints or observations regarding potential IAQ problems and
9) conducting an initial walk through investigation of any IAQ complaints.

Activities and responsibilities for IAQ managers

If the IAQ manager was not involved in developing the IAQ profile, one of the first tasks would be to review the profile. The assignment of responsibilities varies widely among organizations, depending upon the routine activities to be carried out and the capabilities of the available personnel. Maintenance "indicators" are available to help facility staff determine when routine maintenance is required. IAQ complaints can arise from inadequate housekeeping that fails to remove dust and other dirt. Shipping and receiving areas can create indoor air quality problems regardless of the types of materials being handled. Pest control activities that depend upon the use of pesticides involve the storage, handling and application of materials that can have serious health effects. Renovation, redecorating and remodeling activities can create indoor air problems by producing dust, odors, microbiologicals and their spores and emissions. All of these activities should be the concern and supervision of an IAQ manager

2023687697

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

(EPA, 1991).

Periodic commissioning of HVAC systems has been practiced by some full time IAQ managers. These mangers find that not only testing the system and component performances during these periodic commissioning periods, but also checking IAQ and thermal comfort parameters is beneficial in maintaining lower reported complaint numbers.

ECONOMIC COST ASSESSMENT

Ventilation and occupant satisfaction levels

Though the concentrations of pollutants in air were found to be well below levels acceptable under industrial conditions, building occupants kept complaining (Cyfracki, 1990). Different sources present a data defining relationship between the amount of ventilation and the occupants' dissatisfaction: more ventilation means fewer complaints.

Fanger (1988b) established that 15 % of people are dissatisfied when the ventilation rate is 10 L/s per person even if human bioeffluents are the only pollutants present. The percent of those dissatisfied is reduced by nearly a half (to 8%) if the ventilation rate is increased to 20 L/s. A further increase to 40 L/s reduces the number of dissatisfied to 4 %.

Rajhans (1983) reported the following relationship based on more than 2,000 investigations of indoor air complaints conducted in Ontario since 1976:

1) for ventilation rates of 16.5 L/s per person and CO_2 levels of 600 ppm: occasional complaints, particularly if the air temperature rises,
2) for ventilation rates of 10 L/s per person and CO_2 levels of 800 ppm: complaints are more prevalent and
3) for ventilation rates of 7 L/s per person and CO_2 levels of 1,000 ppm: insufficient make up air and complaints more general.

However, many studies exist that have found no relationship between indoor CO_2 concentrations and health effects.

Increasing ventilation rates in existing buildings - energy cost impacts

The energy cost impacts of increased outdoor air flows are dependent on the relative changes in heating and cooling energy occurring at different seasons. The increased cooling energy demand in summer and heating energy demand in winter is counterbalanced by decreases in cooling energy demand in winter and the transitional seasons.

2023687698

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

The effect on annual energy cost depends on the relative magnitude of these changes, the relative importance of the temperature cycles for that climate zone and prices of gas and electricity. The net effect typically results in a marginal increase or a slight decrease in energy costs. Warmer climates will experience a greater energy cost increase due to the larger increase in both sensible and latent cooling loads.

Increasing ventilation rates in existing buildings - system capacity impacts

Building owners and managers face requests by occupants and consultants to raise outdoor ventilation rates to satisfy demands for improved indoor air quality. This requires increasing outdoor air flow rates in existing buildings designed according to previous ASHRAE standards, which allowed lower outdoor air rates for buildings in which there is no smoking (2.5 l/s /occupant or 5 cfm/occupant). A parametric analysis using DOE-2 simulations to generate both energy and indoor air quality data suggested that the energy impacts are minimal, but that system capacity problems are sometimes encountered when ventilation rates are raised in existing buildings (Eto and Meyer, 1988).

Ventilation, occupant satisfaction levels and economics

Cyfracki (1990) analyzed "upscale ventilation" by arbitrarily defining one such system. He evaluated the resulting additional costs, expected reduction in the number of dissatisfied building occupants and the increase in their productivity needed to offset the additional costs. The upscale ventilation system was characterized by two features that enhanced customary post 1973 design:

a) minimum ventilation rate increased from 10 to 20 L/s per person for the whole building and

b) supply air flow increased from 3.0 to 4.6 L/s/m^2 in interior spaces only.

Both features A and B were incorporated into the design of a new typical office building located in Ottawa and the resulting additional costs were calculated. The building consisted of 62% interior and 38% exterior areas. It had a lighting level of 20 W/m^2, an equipment load of 10 W/m^2 and an office population of 7 people/100 m^2. The HVAC system consisted of separate medium pressure VAV units serving one interior area and four exterior areas and perimeter radiation. Air handling units operated 12 hours per day, five days per week and employed a "free cooling cycle". All costs were calculated at the Ottawa 1990 level. The costs of energy were: $0.17 for 1 m3 of natural gas and $0.05 for 1 kWh of electricity, including demand charges. Construction costs were determined by using 1989 "Yardsticks for Costing" with 5% added for inflation from 1989 to 1990.

Feature A doubled the amount of ventilation during summer operation and substantially increased it at low winter temperatures for the combined time of perhaps 5 months per year. For this time, in both

2023687699

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

exterior and interior spaces, the number of people dissatisfied with the indoor air quality was expected to be reduced by half.

Feature B had a two fold effect on the indoor air quality;

1) It increased the amount of ventilation by 50% during most winter operation (perhaps 7 months per year). For this time, in interior spaces, an additional reduction of around 25% in the number of dissatisfied could be expected.

2) It increased the room air motion at work stations by 50% at all times. Based on high frequency of complaints regarding "lack of air", "stale air" and "not enough ventilation", a further significant reduction in the number of dissatisfied, possibly another 50%, could be expected in interior spaces.

The combined benefits of features A and B were likely to result in approximately a 50% reduction in the number of dissatisfied occupants, taking into account the full yearly cycle of operation and the whole building area (interior and exterior).

The estimated increase in productivity of office workers needed to offset the additional cost of the arbitrarily defined upscale ventilation could be estimated in the following manner:

Assume an average office salary of $30,000 per year and 7 persons per 100 m^2, personnel costs would be $2,100/$m^2$. The cost of renting office space can be assumed to be $250/$m^2$. Adding these two figures together results in $2,350/$m^2$ per year as a minimum average productivity cost for each office employee. The ratio of the additional cost of the "upscale ventilation" to the average productivity of office employees is $2.93/$2,350=0.00125.

Therefore, one eighth of one percent increase in the productivity would be sufficient to cover the additional costs. To expect such a modest increase seems to be quite reasonable given the number of complaints about the lack of air and the expected reduction of 50% in the number of dissatisfied occupants. Cyfracki (1990) suggested that the above upscale ventilation features A and B and perhaps some others (like ventilation rates exceeding 20 L/s per person), should be considered for all new construction to reduce problems with indoor air quality.

A major issue is whether those parties involved in the business of office accommodation (occupants, employers, building managers, owners and HVAC professionals) would be willing to support a higher standard of ventilation and potentially higher increases in productivity if it can be provided at reasonably low additional costs. The question that remains is can the increase in productivity be demonstrated? The argument is seductive because the economics of increases in productivity are so favorable, but verification requires evaluation at both health and employee motivation.

2023687700

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Building life cycle costs

Commercial buildings are constructed to house, shelter and support personnel and equipment performing specific functions. Building owners and tenants should be aware that costs other than the initial first cost have significant influence upon the actual total cost of the facility and the productivity of the organization. Because the value of a building is its contribution to the function of the organization, considerations of the real total life cycle cost of a typical building must include:

1) capital or initial costs,
2) operation and maintenance costs and
3) personnel costs.

A number of studies have been conducted by the U.S. General Services Agency (GSA), National Bureau of Standards and B.O.S.T.I. (Figure 3). The GSA and the NBS/B.O.S.T.I. figures are in general agreement concerning the proportions of personnel costs to the total life cycle building costs (Table 12).

Table 12. Proportions of total life cycle costs from two different studies.

	GSA	NBS/B.O.S.T.I.
Personnel Costs	92%	92%
Operation & Maintenance	6%	2.8%
First Cost/Capital Investment	2%	5.2%

The initial investment in HVAC systems is thirteen percent (Figure 4) of the capital costs and the electrical/mechanical costs are twelve percent of the ten year building owning and operational costs. When looking at the total costs of the facilities, the HVAC capital cost is 0.26% and the electrical/mechanical cost is 0.72% of the total. Figures 4 and 5 show in greater detail the life cycle cost for a ten year cycle. The construction and building operational costs are minor compared to the total building costs. If a twenty year cycle was considered, the personnel costs would dwarf building costs to a greater extent. Intelligent investment in the building and operating procedures that produce a more productive work place will be amplified when considering the total building life cycle picture.

2023687701

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

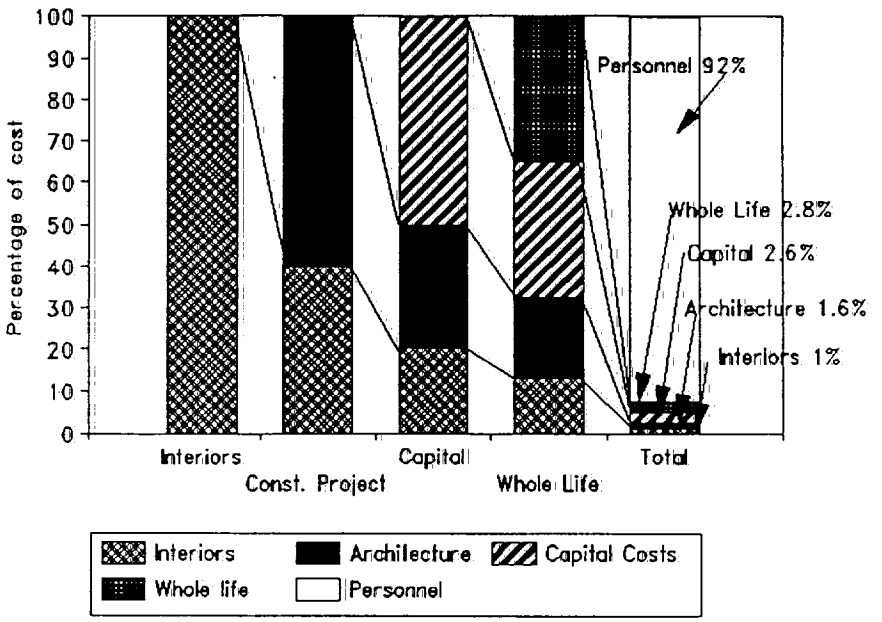


Figure 3. Life cycle cost relationships from B.O.S.T/National Bureau of Standards.

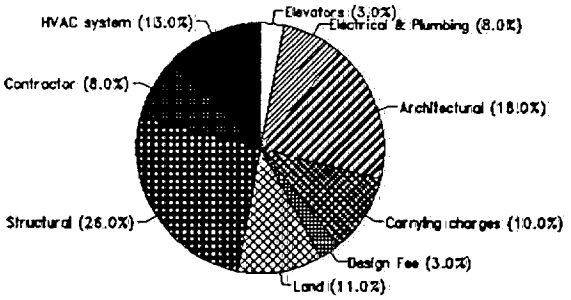


Figure 4. Initial capital costs.

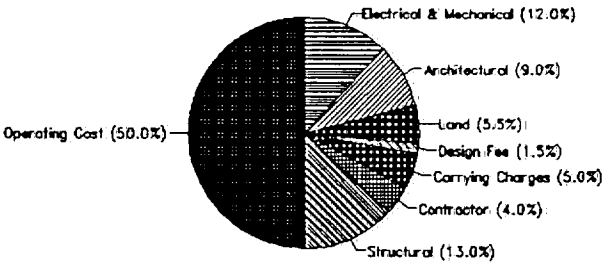


Figure 5. Operation and maintenance cost for ten years.

2023687702

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

TECHNOLOGY - WHAT COMPONENTS ARE AVAILABLE?

COMPONENTS OF AN HVAC SYSTEM

HVAC systems are made up of multiple components such as those shown in Figure 6. These components influence the thermal comfort and air quality of the ventilated space. What follows is a closer examination of various HVAC components and how they impact the system as a whole.

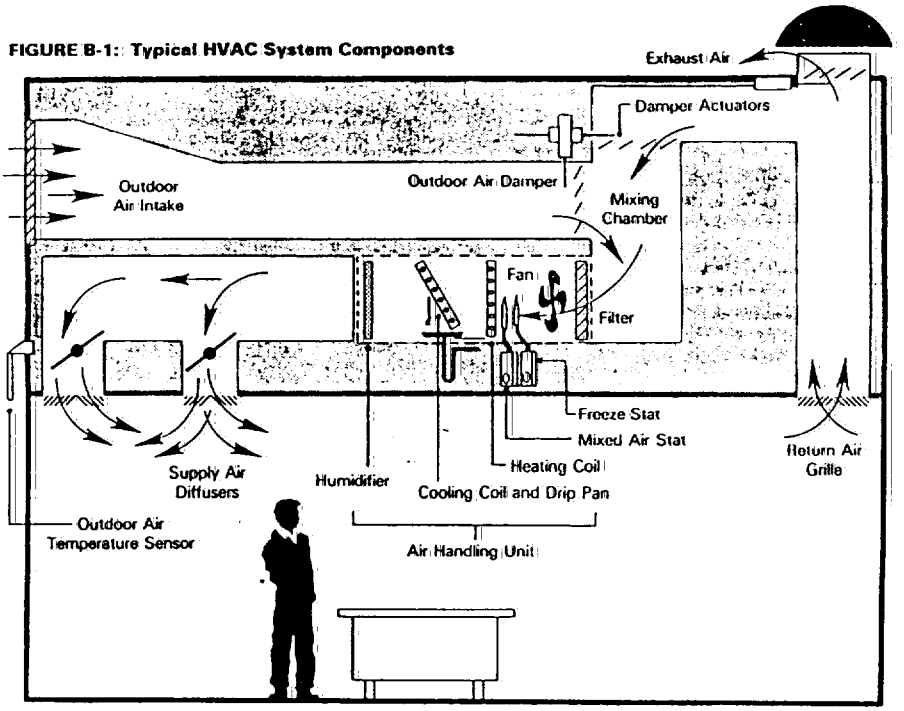


Figure 6. Typical HVAC system components (EPA, 1991).

Outdoor air intakes and building exhausts

The ASHRAE Fundamentals Handbook (1993) provides details on air flow around buildings and recommendations for locating diffusers and exhausts. The ASHRAE Handbook (1992) suggests selection of louvers and the rest of the intake section so the pressure loss is minimized. This is important for preventing precipitation from entering the intake. It also recommends providing drains to prevent the collection of water in the intake ducts. The SMACNA HVAC System Duct Design Manual (1990b) and ASHRAE Handbook (1993) provide tables and figures showing recommended face areas and velocities for air intakes and exhausts. The Air Movement and Control Association Standard 500 (1989) provides

2023687703

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

guidance on test methods for louvers, dampers and shutters.

BOCA NMC M-308.0 Outside Air Exhaust and Intake Openings provides information on locating intakes. It requires intakes to be located at least ten feet from the lot line, other buildings, or the center of a street. It requires that the intakes be located a minimum of 10 feet from hazardous or noxious contaminants such as vents, chimneys, plumbing vents, streets, alleys, parking lots and loading docks. It also requires that the intakes have corrosion resistant screens, louvers and grilles.

Typically, outdoor air intake louvers are designed to accept a face velocity of 400 fpm (2 m/s) at flow rates above 7000 cfm (3300 L/s). At less than 7000 cfm ASHRAE provides further guidance. They are placed in a location where they cannot be seen, such as the roof or backside of the building. Maintenance would include an occasional check of the opening to ensure that it is free of obstructions, dirt, leaves and other debris and that drain lines are open.

In general, intake louver sizing is not considered to be a problem because it is a straight forward part of the design process. Problems arise when contaminated outdoor air is brought into the air handling unit. In several IAQ problem cases, the outdoor air intake was located near a congested road, parking area, loading dock, garbage bins, building exhaust or other contaminant source that allowed the contaminated air into the building.

The problem of contaminated outdoor air due to the siting of the outdoor air intake can be solved through awareness of this as a potential problem during the design process. For existing buildings which already have poorly sited outdoor air intakes, special modifications or relocation of the intake or pollutant sources would be needed. Special filtering of the air would be an option if the source could not be eliminated or the intake relocated. Too many trees and shrubbery near the intake grills can cause breeding grounds for mold and other biological contaminants. Monitoring and regulating the surroundings for pollutant generation should occur.

An extensive amount of research has been conducted on air flow around buildings as noted in the ASHRAE (1993) and it appears to be well understood, but some disagreement exists. General design guidance has been developed and is included in the ASHRAE handbooks but many buildings still end up with poorly sited intakes and exhausts. The BOCA Code is not sufficient to ensure that the intakes and exhausts are cited properly. The standards and codes need to be improved and strengthened based on the guidelines contained in the ASHRAE handbooks.

Dampers and mixing plenum

2023687704

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

The ASHRAE HVAC Systems and Equipment Handbook (1992) recommends using parallel blade dampers for better mixing of the return and outside air streams. It recommends sizing of the outside air damper for 1500 fpm air flow to provide good control. Further, it recommends that the return air duct be placed across the full width of the air handling unit or some sort of air blender be used to promote better mixing of the air streams. Low leakage dampers are recommended for the outside air to help prevent freezing temperatures in the mixed air plenum. Typical construction varies except that usually the return and outside air ducts are perpendicular to each other.

Depending on where the outside air duct connects to the return air duct and AHU, stratification of the two airstreams can result (Rojeski et al., 1992). For a multizone system, this can result in a low concentration of outdoor air in some zones, thus not meeting the minimum outdoor air requirements for that zone.

Additional design guidance and possibly standards and codes may be required to ensure good mixing. For existing buildings, installation of blending devices which promote mixing or modification of the system may be required. Additional research would be needed to complete the understanding of correct and incorrect ducting arrangements.

Total minimum outdoor air control

For an HVAC system with outside, return and exhaust air ducts, the amount of outdoor air should be 15 to 20% higher than the exhaust air to pressurize the building and control in (Rowe, 1988). The latest guidance from ASHRAE in the ASHRAE Air Conditioning Design Manual (1993) recommends that the minimum amount of outdoor air not be increased above the amount needed for dilution of contaminants except to balance the exhaust airflow. ASHRAE suggests that infiltration is more effectively limited through the tightness of the building envelope rather than through pressurization.

ASHRAE 62-1989 provides a table for required minimum outdoor air per person based on specific use patterns of the zone and building. It also provides guidance on determining outdoor air rates based on multiple spaces, intermittent occupancy and ventilation effectiveness. The standard is being revised to add more information and make it more applicable as a code document.

BOCA NMC M-1604 states that the required rate of ventilation shall be continuous during the period the building is occupied, except where otherwise stated. Table M-1604.3 states the required minimum outdoor air in cfm according to the maximum occupancy load per 1000 ft^2. For an office building with 7 people per 1000 ft^2, the outdoor air per person is 20 cfm. Some places, such as stores, have cfm/ft^2 requirements instead of per person. Industry generally follows the ASHRAE and BOCA guidance on minimum outdoor air flow rates although some states, municipalities and other organizations

2023687705

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

do not.

Many different outdoor air flow rates can occur from zero during unoccupied periods, to minimum during occupied periods when the outdoor air temperatures are very high or low, to 100% outdoor air when an economizing condition exists. The sensors, controls, actuators and dampers will require periodic checks to confirm that they are operating correctly and adjustment, calibration and replacement if operating incorrectly. The minimum outdoor air flow rate also needs to be checked to confirm that it meets the requirements.

Variable air volume systems sometimes are commissioned incorrectly so that the minimum outside air is set at medium or high total air flow. When the system operates in the minimum total air flow condition, the minimum outside air would be less than required. Improper control of return or relief fans in a variable air volume systems can change air pressures in the AHU and force air out the outdoor air duct or reduce the amount coming in enough that the minimum outside air is not met. Several techniques are used to control return fans although the flow matching technique is probably the best.

Ensuring that the minimum amount of outdoor air is introduced into a building and that proper air distribution is achieved is not particularly straight forward. The ASHRAE Air Conditioning Systems Design Manual (1993) suggests that pressurizing a building to offset infiltration is not necessary. Without building pressurization, air will not move through the return duct system unless the ductwork is extremely oversized or return fans are used. These alternatives are not always economical or practical. If building pressurization is to be used as a means to help ensure adequate air distribution through the return air system, should the amount of outdoor air be 15 to 20% higher than the exhaust air to effectively pressurize the building (as suggested by Rowe, 1988)? Systems with return fans may require a smaller percentage as dictated by the accuracy of the airflow measuring instrumentation. In systems without airflow measuring instrumentation, this percentage, although conservative, may be appropriate. Still, designer attention is warranted in either case to help ensure that rules of thumb are not used out of context. This suggests the need for guidelines describing specific design procedures that extends typical duct sizing procedures to include analysis of the performance of the entire air distribution system including the air handling unit and dampers (such as the minimum OA damper). Further guidance on the correct commissioning, operation and maintenance procedures also would be needed.

During major cleaning activities, such as carpet cleaning or floor polishing, the HVAC system may need to be operated under elevated minimum outside air conditions to remove pollutants. This should be covered sufficiently in BOCA 3307.0 Health Hazards, which states that every construction or maintenance activity which results in the diffusion of dust, stone and other small particles, toxic gases or other harmful substances in quantities hazardous to health shall be safeguarded by means of local ventilation or other protective devices to insure the safety of the public as required by the regulations of

2023687706

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

the administrative authority.

In some cases where the outside air intake for an AHU was improperly located near a loading dock, the only alternative may be to close down the OA dampers during deliveries to prevent the intake of combustion gases. This may require a previous period of higher ventilation rates to dilute contaminant concentrations in the building.

Installation of flow sensing and control devices in the outdoor air stream may be required to control the dampers so that the minimum OA quantity is brought into the AHU. It may be possible to measure the outdoor, return and mixed air temperatures, or enthalpies, to determine the percentage of outdoor air and control the dampers. A constant speed fan, placed in the outside air duct, can be used to control the amount of outdoor air, although the amount will not be constant as the fan curve rides the system curve (with changes in AHU damper position, etc.).

AHU Media particulate air filters

ASHRAE 1992 HVAC Systems and Equipment Handbook discusses air cleaners for particular contaminants. ASHRAE 1993 Fundamentals Handbook contains information on typical design air velocities for filters. The guidelines discuss the efficiency of the filter to remove particles of a given size and the amount of energy needed to pull or push air through the filter. ASHRAE Standard 52.1-1991 Method of Testing Air Cleaning Devices Used in General Ventilation for Removing Particulate Matter provides methods for determining filter efficiency, resistance and dust holding capacity. An updated version of Standard 52.1-1992, but cannot effectively be applied to meet ASHRAE Standard 62-1989 (Fencl, 1993).

In typical HVAC applications, filters are installed in the AHU to remove large particles which would otherwise clog heating and cooling coils and impede the operation of the HVAC system. High efficiency filters are usually only used for clean rooms, hospitals and other areas where a clean environment is required.

As the filter loads up with particles, it becomes more efficient at particulate removal but the pressure drop across the filter increases causing a reduction in system air flow. The pressure drop across the filter can be easily monitored using pressure sensors. Air filters require some level of maintenance and replacement depending on the type. Some can be cleaned but most are replaced after a certain length of time or after a specific pressure drop is experienced across the filter.

Air handling units and air filters are sometimes located in difficult to reach places, such as ceiling plenums and become prone to low maintenance activities. Filters which are left in too long can severely

2023687707

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

restrict airflow and cause ventilation problems. Severe clogging can result in unfiltered air bypassing the filters and clogging the coils. If the pressure becomes high enough, the filters themselves can fall apart and clog the coils more. Air filters can be a breeding ground for biological contaminants if the filter becomes wet. The low efficiency filters are not designed to remove fine particulate matter such as, bacteria, or respirable particles under 3 micons in diameter let alone gases and VOCs.

Improved AHU design guidance, standards and probably codes are needed to improve the accessibility and maintenance of air filters. Medium and high efficiency particulate air filters can be installed to remove respirable particles. Additional air cleaning equipment such as electronic and carbon filters could be used and are covered in the chapter on Air Cleaning and Equipment.

Heating and cooling coils

SMACNA HVAC Systems Duct Design Manual (1990b) and ASHRAE Handbook (1993) contains information on typical design air velocities and pressure drops for heating and dehumidification coils.

The outside surface of coils require periodic cleaning to prevent clogging and improve heat transfer. Dirty coils not only reduce the cooling capacity but if severely clogged may increase the face velocity of air passing through the coil. This would force condensed moisture into the ducting and provide areas for bio growth. The fluid flowing in the coils should be treated to prevent rusting and scaling of the coils which would inhibit heat transfer and cause loss of capacity. Dirty and improperly sized coils lack the capacity to cool or heat the building and would reduce or prevent the flow of outside air into the building.

Malfunctioning coil controls can result in thermal discomfort. If coil drain pans become clogged or do not drain properly they can promote the growth of molds and bacteria. Improperly trapped drain lines permit the drain to dry and thus allow contaminated drain line air to flow into the AHU.

While the modeling of heating coils is a relatively mature science, modeling the dehumidification process of a chilled water coil is not well understood. An improved model of the latent heat transfer process of cooling coils would lead to a better understanding of how to design coil based dehumidification systems. A better understanding of how cooling coils affect the growth of biological contaminants is needed so that guidelines on designing, operating and maintaining cooling coils can be developed. Questions such as airflow, setpoint temperatures and chilled water temperature should be investigated.

Humidification/Dehumidification

ASHRAE (1992) indicates that at 50% RH, the mortality rates of certain organisms are highest

2023687708

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

and the influenza virus loses much of its virulence. The handbook describes the method and calculations for using air washers, coils and desiccants to dehumidify air. SMACNA HVAC Systems Duct Design manual (1990b) and ASHRAE Handbook (1993) contains information on typical design air velocities for air washers and dehumidification coils. Proper dehumidification can only take place when the chilled fluid is below approximately 45 °F.

ASHRAE STANDARD 55-1981 provides guidance on acceptable temperature and humidity conditions. It recommends that the humidity should be kept between 30% and 60%. An addendum to Standard 55 was issued in 1993 which raised the allowable humidity level. ASHRAE STANDARD 62-1989 states that the relative humidity in habitable spaces should be maintained between 30% and 60% RH to minimize growth of allergenic and pathogenic organisms. ASHRAE STANDARD 62-1989 states that steam humidifiers are the preferred type of humidification if care is exercised with boiler water chemicals and steam additives.

BOCA NMC M-1903.3 Humidity requires that the indoor design relative humidity for heating not exceed 30%. For cooling, the actual design relative humidity within the comfort envelope as defined in ASHRAE Standard 55 shall be selected for the minimum total heating, ventilating and air conditioning system energy utilization.

The humidifiers need to be cleaned often to prevent scaling and the growth of biological contaminants. Steam humidifiers have been noted as causing IAQ problems when the chemicals added to the water are not properly administered. Because of this, the steam humidifiers should use clean water rather than treater boiler water. Improperly operated and maintained humidifiers can wet ductwork and provide areas conducive to microbiological growth.

A common scheme for energy conservation is to heat only, cool only, or ventilate only during different times of the year. With the concern about high moisture in the ducting and rooms, this control scheme may not be appropriate. The ventilation only mode usually occurs in the spring and fall; during the mild temperature periods when heating or cooling of the building can be done by using outside air. Unfortunately, the spring and fall can have high relative humidity levels and under some conditions may produce high humidity levels in the ducting and rooms which could offer good growth areas for biogens.

ASHRAE recommends controlling the relative humidity but codes do not recommend dehumidification. Improvement of the codes would be beneficial. An examination of the cost\benefits of humidity control needs to be conducted to provide information to designers, architects, owners and managers.

Ducting

2023687709

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

SMACNA (1990b), ASHRAE (1992) and Air Conditioning Contractors of America, ACCA, provide similar guidance on the size of ductwork. Additionally there are numerous software packages for sizing ductwork. Exhaust systems conveying particulates are sized for a constant air velocity. The interior of ducts may need to be cleaned occasionally, depending on the amount and kind of particulate matter deposited on the duct. Duct lining, especially wet fibrous lining, provides an ideal breeding ground for biological growth. Fibrous duct lining can also break apart adding to the particulate concentration in the building.

Duct systems must be properly sized to help ensure proper air distribution. When the installed duct system does not match that of the design air flow, problems can occur. Air distribution problems can occur, particularly at the end of duct runs, if departures from the original design increase the friction losses to a point that approaches the limit of the fan performance.

The T-method of duct sizing is a relatively new design procedure which optimizes duct design by minimizing an objective function which includes initial cost, energy cost, hours of operation, annual escalation, interest rates and amortization period.

Duct cleaning is a relatively new concept which uses vacuums to remove particulate matter. The intended benefit is usually to remove the particles so that they do not get blown into the space, or remove contaminants, such as biological contaminants, which might be in the duct. An additional benefit of duct cleaning would be an improvement in air flow and energy efficiency. A new standard exists for testing the effectiveness of cleaning metal ducting. Overall, research needs to be conducted to understand the costs, benefits and procedures of duct cleaning.

Many studies have cited problems with microbiological growth in fibrous ducting and duct liners when they become wet. Due to the problems with fibrous duct linings, standards and codes are needed to guide and regulate its use.

Duct leakage can cause several problems including drawing contaminants into the return duct and reducing airflow into the zones. Leaks in cold air ducts, in hot and humid ceiling plenums can cause condensation and possibly mold growth.

Plenums

SMACNA HVAC Systems Duct Design manual (1990b) provides guidance on the sizing of extended and semiextended duct plenums. BOCA NBC 2805.0 and NMC M-303 PLENUMS define plenums as an enclosed portion of the building which forms part of an air distribution system. They limit plenums to uninhabited crawl spaces, areas above the ceiling and below the floor, attics and mechanical

2023687710

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

rooms. They state that fuel fired equipment shall not occupy plenums and place requirements on piping, material, ducts and wire tubing in plenums.

Return air plenums can easily cause air flow problems in buildings if the HVAC system is not designed and balanced correctly. Further airflow problems can occur when partitions are added and room layouts are changed.

Control Systems

The controls system is one of the most important components for the HVAC system. Inadequate control performance can result in poor temperature control, poor humidity control and poor ventilation control. Many advances have been made in the controls area to improve the performance and reliability of control systems. Direct digital control systems are now widely used and can incorporate many strategies which could help improve IAQ. DDC can use Proportional Plus Integral and Proportional Plus Integral Derivative control algorithms to maintain setpoints as opposed to the older pneumatic technology which typically used proportional only control which seldom maintained the setpoint of a HVAC process. DDC systems can also use innovative strategies to conduct flushing of building air during the nighttime to remove a buildup of contaminants. Control systems can incorporate air flow measurement arrays which could measure the outside air flow and adjust the damper positions to bring in the correct amount of outside air.

ENVIRONMENTAL SENSORS AND CONTROL

In the past two decades, energy conservation measures have resulted in tighter buildings and reduced ventilation rates. New construction techniques, new materials, machines and consumer products that produce many new contaminants also have been introduced. These developments have led to an increased concentration of airborne contaminants in the indoor environment and an increased concern for IAQ in residences, offices and other nonindustrial environments.

Major indoor air pollutants include radon and radon daughters, ETS, biological contaminants, asbestos, volatile organic compounds (VOCs), particulate matter, PAH, pesticides and combustion gases (EPA, 1989). Assessment of these air contaminants is important for evaluating the effectiveness of engineering control measures (source management, ventilation control, air cleaners) and for determining compliance with IAQ standards. Epidemiology of diseases of environmental origin and many other areas of research associated with environmental health are dependent upon accurate evaluation of indoor air contaminants and exposures to these contaminants.

This section is a review of literature on measurement of thermal comfort variables and indoor air

2023687711

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

quality parameters. Current information and state of the art of measurement techniques of indoor air quality, thermal comfort parameters and other airflow variables are covered. Research and development needs also are addressed for the attention of both the EPA and others that support the IAQ research effort.

Measurement of thermal comfort parameters

Thermal comfort variables include air temperature, radiation, humidity and air movement (ASHRAE, 1993). The perception of comfort, temperature and thermal acceptability is related to one's metabolic heat production, its transfer to the environment and the resulting physiological adjustments and body temperatures. Heat transfer is influenced by the environmental factors of air temperature, thermal radiation, air movement and humidity. This section discusses the state of the art measurement methods for each thermal variable. Related factors such as turbulence intensity, airflow patterns and air exchange effectiveness also are considered.

Air temperature

Traditional techniques for measuring air temperature include the thermal expansion thermometers and thermocouples. Temperature sensing devices that utilize thermal expansion include liquid in glass and bimetallic thermometers. Traditionally, temperature has been controlled by thermal expansion thermometers. These techniques are still used widely today.

Advances in solid state devices, precision manufacturing techniques and microelectronics have resulted in the wide use of resistance thermometers such as the thermistor and resistance temperature detector (RTD). These devices exhibit changes in electrical resistance with changes in temperature. While the thermocouple is probably the most versatile temperature transducer, the RTD is the most stable and the thermistor is the most sensitive. Both thermistor and RTD offer high sensitivity and tight tolerances to permit interchangeability and ruggedness. Thermocouples and resistance thermometers are used widely for monitoring and control applications.

A recent innovation in thermometry is the integrated circuit temperature transducer. This unit outperforms many traditional temperature measuring devices (Simpson et al., 1991). It is available in both voltage and current output configurations. Each configuration supplies an output that is linearly proportional to absolute temperature.

Mean radiant temperature

Mean radiant temperature is as important as air temperature in affecting heat loss and comfort

2023687712

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

(ASHRAE, 1993). For indoor environments, when air movement is low, the operative temperature is approximately the average of air temperature and mean radiant temperature.

Mean radiant temperature can be determined by measuring temperatures of surrounding surfaces and determining the angle factors from existing diagrams (Fanger, 1973; ASHRAE, 1993). However, this method is difficult and time consuming. Mean radiant temperature also can be determined by using a globe thermometer or a two sphere radiometer (ASHRAE, 1993). A globe thermometer consists of a hollow sphere 150 mm in diameter, flat black paint coating and a temperature sensor at its center. The temperature assumed by the globe at equilibrium results from a balance between heat gained or lost by radiation and by convection.

A two sphere radiometer consists of two spheres approximately 50 mm in diameter; one is gold plated, the other is black. The spheres are heated electrically to the same temperature to eliminate differences in convection. The difference in energy required to maintain temperature equilibrium is measured and from this difference, mean radiant temperature of the space is calculated.

Cost effective radiant sensors are under development. These will measure radiant temperature and, as a result, allow mean radiant temperature to be determined (Culp et al., 1993). Silicon infrared sensors have been built using micromachining technology that offer high reliability and low cost. Alternative technologies to measure infrared radiation include bandgap semiconductor materials (such as mercury cadmium telluride) and pyroelectric devices.

Air velocity

Air velocities in occupied zones usually are small (0 to 0.5 m/s) but have an effect on human thermal sensation (ASHRAE, 1993). Air velocity measuring devices include pitot tubes, vane anemometers, thermal anemometers and airborne tracer techniques. Pitot tubes and vane anemometers are simple and convenient methods to measure air velocity; however, they are not sensitive enough for measuring low velocities common in indoor environment. Tracer techniques are suitable for measuring velocity in an open space. Typical tracers include smoke, feathers, pieces of lint and radioactive or nonradioactive gases (ASHRAE, 1993). Measurements are made by timing the rate of movement of solid tracers or by monitoring the change in concentration level of gas tracers. This method is awkward to use but may be valuable in tracing air movement.

Thermal anemometers contain a sensing element that is heated electrically and exposed to an airstream. Very low air velocities can be measured with thermal anemometers. Most thermal type transducers collect particles that will cause a calibration shift. What is needed is a low cost, reliable velocity transducer that is sensitive to low air velocities and will work for years with a minimum of

2023687713

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

maintenance and calibration (Rask and Agarwal, 1989). Also needed are reliable low cost velocity transducers for control applications.

Humidity

A wide range of instruments and sensors are available for measuring air humidity. These include the psychrometers, dew point hygrometers, dimensional change hygrometers, electrical impedance hygrometers, electrolytic hygrometers and gravimetric hygrometers.

No single instrument meets the requirements for all applications. Some sensors work best at high humidities and others at low humidities. Also, most of the current humidity sensors fail to give accurate readings above 90 or below 10%. There is a need to develop a sensor that would be applicable over a wide range of humidity and one that will maintain its accuracy over several years of service without regular maintenance.

Fahlen, (1993) indicated that capacitive humidity sensors are well suited for the control of humidity levels in buildings. The combined error of linearity, hysteresis and repeatability normally is below 5% RH at 20°C. The cross sensitivities to variations in temperature and power supply (voltage and frequency) are acceptable and the cross sensitivities to hydrocarbons, carbon dioxide and environmental tobacco smoke are negligible.

Turbulence intensity

The effects of velocity fluctuations are not understood completely; however, indications are that the fluctuations (expressed by turbulence intensity), in addition to the mean velocity, are important in human sensation to draft (ASHRAE Handbook, 1993). For humans, high turbulence was more uncomfortable than low turbulence (Fanger et al., 1988).

The degree of turbulence may be expressed in terms of turbulence intensity, which is defined as the standard deviation of velocity divided by the mean velocity. Turbulence intensity may be determined by measuring the instantaneous velocities over an interval period of time with thermal anemometers. As noted above, thermal anemometers that have frequency responses adequate for getting airflow turbulence information are not rugged enough even for research environments.

Flow patterns

Room airflow patterns may be visualized by either the smoke or bubble method. Smoke generating methods have been used for many years to trace airflow patterns in rooms. A popular

2023687714

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

material, which is non toxic and stays with the airstream well, is titanium tetrachloride, a liquid that combines quickly with air to form a dense white smoke. Smoke also can be generated by heating mineral oil with a pesticide fogger or from a heated wire.

Neutrally buoyant bubbles also may be used to visualize the flow. These bubbles can follow complex laminar and turbulent airflows. This method has been used to visualize simple and complex flow patterns (Hale et al., 1971; Lawson, 1978; Timmons et al., 1980). Disadvantages of this method include: (1) setup is cumbersome and stationary, (2) bubbles usually must be tracked only in a plane and (3) setup interferes with normal lighting within the room.

Air exchange effectiveness

Outside air taken into an occupied zone of a building cannot be assumed to be perfectly mixed with the indoor air, as this mixing is affected by various factors such as supply and return type and location, outside airflow, mode of operation and the presence of indoor partitions, equipment and occupants. The actual amount of outside air distributed into the occupied zone can be substantially less than that measured at the air handling units. Thus, air change effectiveness is an important variable that should be measured as part of an indoor air quality study.

Air change effectiveness can be determined using the tracer gas decay technique (Yocom and McCarthy, 1991; ASHRAE, 1993). Tracer gases include helium (He), nitrous oxide (N_2O), carbon dioxide (CO_2), carbon monoxide (CO), sulfur hexafluoride (SF_6) and perfluorocarbons (PF). SF_6 and PF are used most frequently. While it is true that each of the tracers above is extremely unreactive, it is not certain that they do not adsorb on or emanate from indoor sources. More research clearly is needed in this area. A technique for field measurement of air change effectiveness of various types of ventilation systems should be developed.

Measurement of IAQ parameters

A wide variety of measurement techniques and instrumentation systems are available for the major indoor air pollutants. For a number of the major pollutants, EPA and/or other organizations have developed protocols that standardize the monitoring procedures. For some pollutants, however, generally accepted protocols have not been established. In this section, measurement techniques for the major indoor air pollutants are discussed.

Gases and vapors

Existing instruments for measuring gases and vapors utilize one of the following: infrared and

2023687715

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

ultraviolet radiation, flame and photoionization, electrochemical reactions or chemiluminescence. Instruments of this type are available for sulfur dioxide (conductimetric, amperometric and flame photometric); carbon dioxide and carbon monoxide (nondispersive infrared and electrochemical); nitrogen dioxide, nitrogen oxide and ozone (chemiluminescence); hydrocarbons (flame ionization); and for a host of other substances with the use of a gas chromatograph utilizing a variety of sensors (Yocom and McCarthy, 1991).

Fahlen (1993) evaluated two CO_2 sensors. These sensors showed acceptable performance for control purposes with a deviation of less than 50 ppm at a level of 1000 ppm. However, sensor calibration and/or adjustment was a time consuming process. These sensors also were sensitive to humidity below a threshold level.

Fahlen (1993) tested five mixed gas sensors. These sensors showed a mixed behavior; some reacted strongly to tobacco smoke, some slightly and one hardly at all. All were sensitive to humidity. Tests with varying compositions of the chosen VOC cocktail indicated little difference in response to individual components.

Airborne particulate matter

Airborne particulate matter may be categorized into: (a) total particulate matter, (b) inhalable particulate matter (diameter is smaller than approximately 10 um) and (c) respirable particulate matter or RPM (generally less than 3 um). RPM is that fraction of the ambient particulate matter capable of penetrating through the airways of the lower respiratory tract (tracheobronchial tree) of healthy adults and can deposit in those portions of the lungs (alveoli) not protected by ciliary action (Miller et al., 1979).

Various techniques are available for measuring airborne particulate matter concentration and particle size distribution. These include gravimetric samplers, piezoelectric sensors and optical particle counters.

Use of gravimetric methods is a long standing procedure for air pollution control purposes. In industrial hygiene practice and for indoor air studies, gravimetric methods have displaced counting methods for all mineral dusts except asbestos and other fibers. Samples are collected on preweighed membrane filters, often with a size selecting, first stage cyclone and reweighed after suitable temperature and humidity conditioning.

Airborne particle mass concentration may be measured by depositing the particles on a piezoelectric sensor by electrostatic precipitation. The change in the resonant frequency of the sensor is directly proportional to the mass of deposited material. At a constant air sampling rate, particle mass

2023687716

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

concentrations are proportional to the rate of change in frequency. This instrument is capable of measuring particle concentrations in air as low as a fraction of milligram per cubic meter at a sampling rate of 1.0 L/min over a 2 minute sampling period.

Optical particle counters (OPC) detect and size particles using light scattering. They count light pulses scattered from particles that flow, one by one, through an intensely illuminated sensing zone. Sampling rate is low and for conventional white light particle counters, the smallest detectable particle size is 0.3 um. Laser particle counters are capable of measuring particles as small as 0.1 um in diameter. A condensation nucleus counter can count submicrometric particles to below 0.01 um.

Testing for function and calibration of existing instruments, especially optical particle counters, is difficult, time consuming and costly. No standard aerosols are available for calibration purposes. Monodisperse polystyrene spheres are aerosolized for calibration of automatic particle sizing instruments, but they hardly constitute a calibration aerosol in the fullest sense.

Bioaerosols

Bioaerosols are airborne particles, large molecules, or volatile compounds that are living or were released from a living organism (ACGIH, 1989). They may cause human disease, immunological disorders and respiratory infections. Bioaerosols of major concern for indoor air quality are bacteria, endotoxins, fungi, viruses and antigens. Because bioaerosols are so diverse, the sampling and analytical techniques for measuring them are also diverse.

There are three general methods (Burge and Solomon, 1987) of air sampling for assessment of biological contaminants: gravity samplers, inertial impactors and devices. Gravitational collectors consist of a collection plate which contains a growth medium. As it monitors only particles that fall out of suspension, this method is not volumetric and produces a qualitatively biased picture of the air spora. Thus, accurate site to site and time to time comparisons cannot be made.

Inertial impactors operate by either pulling air across a culture plate or by rotating the plate through the air at a constant speed (Yocom and McCarthy, 1991). Included in this category are slit impactors, sieve impactors or cascade impactors and liquid impingers. Slit impactors operate by rotating a plate containing a culture medium. Cascade impactors draw air through a series of sieve plates of smaller and smaller caliber; culture plates are placed under each sieve plate and the microorganisms are impacted on them. Liquid impingers draw air through a liquid trapping the particles.

Following collection of an air sample of bioaerosols, analysis of the media is done using either the culture methods or particle methods (EPA, 1989; ACGIH, 1989). For cultural assays, the organisms

2023687717

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

are collected on media which will support the growth and identification of certain types of microorganisms. Colonies are counted with a microscope and reported as colony forming units (CFU/m3). Particle methods involve visually counting and identifying the biological aerosols, or analysis using biochemical or immunological assays.

Sampling for bioaerosols requires a very specialized expertise. The researcher must have experience in selecting the appropriate sampling methodology and collection media, collecting a representative sample, using a qualified laboratory to perform the analysis and interpreting the results. Thus, existing methods and devices are not only time consuming but also expensive. For assessing and characterizing bioaerosol concentration in the indoor environment, real time, portable instruments should be developed.

Control strategies

Control strategies for some of the contaminants are well researched. There is a need to develop control strategies for all contaminants. A systematic investigation of the best "integrated" control strategy would allow designers and building operators to make rational decisions.

Control strategies that have been developed for radon include: (1) passive techniques (e.g., sealing cracks), (2) active sub slab depressurization techniques and (3) ventilation (e.g., dilution, pressurization, etc.). These techniques were developed for school buildings (Menetrez and Kulp, 1993; Geomet, 1991). Although experiences in other types of buildings are limited, Menetrez and Kulp (1993) noted that diagnostic and mitigation techniques developed by EPA for schools can be used as a basis for developing diagnostic and mitigation techniques for other buildings.

Passive techniques involve construction practices (e.g., sealing cracks, slabs, etc.) to minimize/prevent entry of radon in the building envelope. Prior to construction, incorporating active sub slab depressurization (ASD) techniques into the foundation is the most cost effective means of dealing with significant onsite radon potential (Menetrez and Kulp, 1993). However, for established buildings with a large ground contact area that is finished with flooring, furnishings, etc., and occupied, ASD may not be preferred or reasonable.

In some cases, radon can be controlled by using an adequate amount of outside air to dilute radon levels (ventilation). By pressurizing the system, radon entry may also be minimized or prevented. These methods have been found to work well in residential houses and in schools. Not all systems, however, can provide building pressurization. Many of the all air systems and some of the all water systems are desirable for building pressurization; many of the unitary systems and all of the all water systems, on the other hand, will not allow pressurization.

2023687718

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

AIR CLEANING AND FILTRATION EQUIPMENT

Indoor air quality may be controlled through one or more of the following means: source control, ventilation control and air cleaning. The principles involved in each of these control strategies and the range of indoor air concerns to which they can be successfully applied have been presented elsewhere (EPA, 1989).

The goal of air cleaning and filtration equipment is to reduce or eliminate unwanted particles or gases from the air supplied to ventilated space (Croome and Roberts, 1981). Air contaminants include dusts, smokes, fumes, dry granular particles, fibers, gases, bacteria, mold spores and pollen. These may range from diameters of molecular size up to 5000 microns (μm). Air filtration is usually concerned with the range of 0.1 - 100 μm size particles. Figure 7 presents some of the common particulate contaminants found in air and their size.

Dust, smokes and fumes are solid particulate matter. They are differentiated based on their various sizes. Dust is generally classified as below 80 μm in size and may be comprised of soot and smoke, minerals such as rock, metal and sand, organic materials such as wool, hair, lint and plant fibers and mold spores and pollen. Smoke particles are generally about 0.3 μm and below in size. It is a suspension of fine particles produced by incomplete combustion of organic substances (e.g., coal and wood, or finely divided chemical compounds released into the atmosphere). Fumes are particles below 0.1 μm in size and are formed by condensation of vapors.

Nonparticulate contaminants include vapors condensable at normal pressures and temperatures and permanent gases. Permanent gases such as SO_2 and other sulfur oxides are troublesome because they form acidic solutions on contact with moisture (Croome and Roberts, 1981).

Filters

Filters designed to remove the various types of contaminants mentioned can be classified in the following groups according to ASHRAE Handbooks HVAC Systems and Equipment, 1992 and HVAC Applications, 1991:

1) viscous impingement type panel filters,
2) dry type extended surface filters,
3) viscous impingement type moving curtain filters,
4) dry media moving curtain filters,
5) electrostatic air cleaners,
6) air washers/absorbers and
7) adsorbers.

2023687719

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

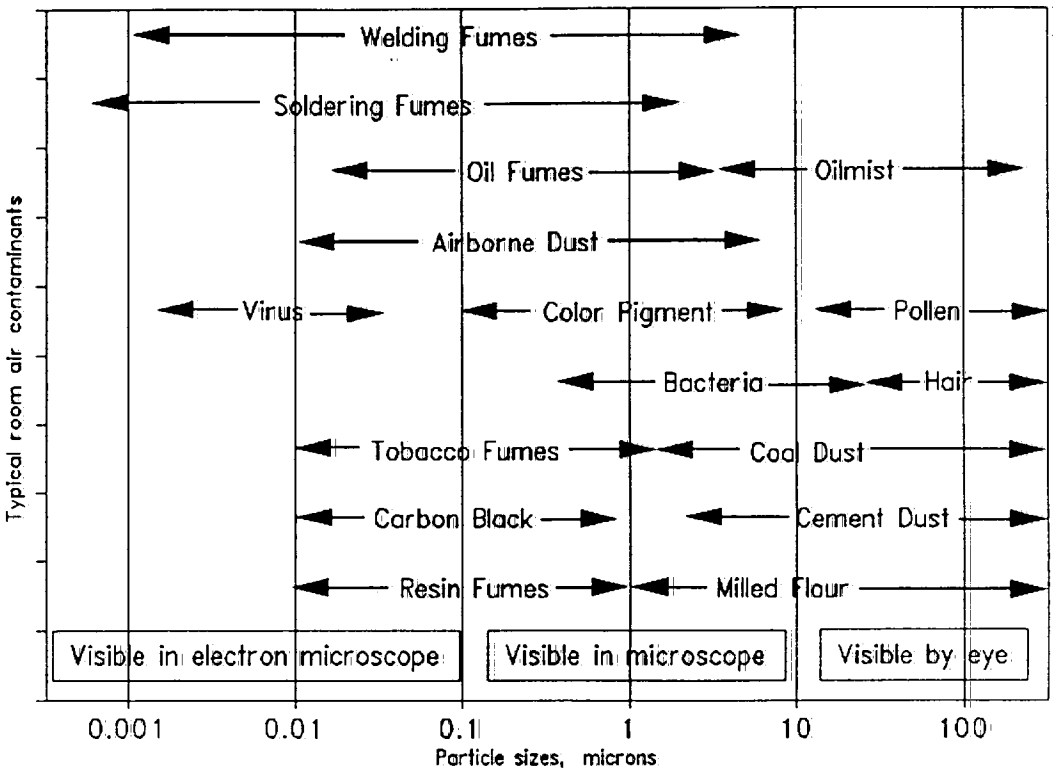


Figure 7. Particulate size of various contaminants

Viscous impingement filters utilize relatively coarse filtering media of fiber, wire, screen, mesh, metal stamping or plates coated with a viscous substance such as oil or grease. The unit panel filters may be permanent or disposable and operate at face velocities of 200-800 fpm. The dust holding capacity of these filter types is high and the typical resistances range from 0.2 iwc to 0.5 iwc. They are generally used in residential furnaces and air conditioners and often as a prefilter for higher efficiency filters.

Dry type extended surface filters utilize random fiber mats or blankets consisting of glass fiber, cellulose fibers, wool felt and various synthetic materials. The efficiency of dry type filters is usually higher than that of panel filters. Initial resistance of dry type filters range from 0.1 to 1.0 iwc. The filters should usually be replaced when the resistance reaches 0.5 to 2.0 iwc. The resistance increases with the collection efficiency of the filter. One type of dry, extended surface filter is the pleated panel type dry filter which is typically supplied as the "factory furnished" filters which come with most packaged HVAC equipment. This filter is not designed with the intent of preventing humans from breathing particles bad for them. This filter is designed with the intent of preventing the fan and coils

2023687720

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

from being exposed to the very large particles and fibers which could damage or clog it. The filter has no real effect on indoor air pollution (SMACNA, 1990a). The pleated type filters have a DOP efficiency below 30%. Electret filters are composed of electrostically charged fibers which augment the collection of smaller particles. There DOP efficiency range is from 30% to 98%. High Efficiency Particulate Air (HEPA) filters have a much higher efficiency than the pleated filters and can have a DOP efficiency of 99.97% or greater. Ultra low penetration air (ULPA) filters have an even higher DOP efficiency of 99.999% and are used for cleanrooms and toxic particulate collection. Duct velocities for the extended surface dry type filters run from 250 fpm for the HEPA and ULPA filters to 750 fpm for the pleated panel filters.

Viscous impingement type moving curtain filters utilize random fiber media which is coated with a viscous substance such as oil or grease. Some moving curtain filters are furnished on a roll which supplies new media according to time, pressure drop or light transmittance. A second type of moving curtain filter consists of metal mesh media panels installed on a traveling curtain which passes through a adhesive reservoir where the dust is removed and new adhesive is applied. The moving curtain filters typically operate at face velocities of 500 fpm. The dust holding capacity of these filter types is high and the typical resistances range from 0.4 iwc to 0.5 iwc.

The dry type moving curtain filters utilize random fiber or wire mesh media of relatively high porosity. The filters typically operate at duct velocities of 200 fpm. The filters are often used in textile mills and dry cleaning processes for the collection of lint and in press rooms for the collection of ink mist.

Electrostatic air cleaners (EAC) work by using a two stage process. Contaminating particles are ionized by passing them through an electrostatic field of 6 to 25 kV DC potential. The particles are then collected on oppositely charged plates, which may be coated with an adhesive. Face velocities are about 300-500 fpm, with average efficiencies of up to 98% for 150 to 350 fpm airflow. Electrostatic filters require routine cleaning or the effectiveness drops. These filters are usually cleaned using hot water sprays operating at high pressure during an "off" (cleaning) cycle and may be carried out manually or automatically. If operated improperly, they can increase indoor air pollution by ionizing the air and converting the O_2 into O_3 (Ozone). The problem is exacerbated by the fact that both collector efficiency and ozone production rate are roughly proportional to power input (Viner et al. 1992).

The charged media filter is a panel filter made from disposable, dielectric material. When a high DC voltage is applied to it, an electric field is created. These filters operate at about 250 ft/min with a resistance that varies from 0.1 in w.g. (clean) to 0.5 in w.g. (dirty).

Self charging media filters are a hybrid of both media filters and electrostatic filters. They work

2023687721

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

by using the air moving through them to create a static electric charge. This is the same effect as when a balloon is rubbed on a sweater. However, the electric field developed is very small and these are only slightly more efficient than panel filters.

The adsorption type filter, containing activated carbon or similar materials, is used to remove various gases and odors and can be reactivated by heating. Prefilters are generally required for dust removal. Most of the gases to be removed normally are volatile organic compounds (VOCs). Often, air cleaners employ filters along with an adsorption bed for combined pollutant removal. The activated carbon beds are normally placed down stream of the filters. The use of activated carbon bed filters have limitations. Some of these limitations as listed by McNall (1975), Ramanathan et al. (1988) and Ensor et al. (1988) are:

1) Small quantities of carbon used in panel and duct filters appear to have limited usefulness in controlling indoor air VOCs at the extremely high face velocities often encountered.
2) Charcoal has a finite capacity; after which, heavier molecules usually replace lighter ones and release lighter ones into the downstream air.
3) Carbon has a finite useful lifetime and must periodically be replaced. For some organics this lifetime is short.
4) Control of low level VOCs appears to be difficult with conventional carbon adsorption technology.

Kinkead (1990) reports that studies conducted at Lawrence Livermore Laboratory proved that the solvent capacity of activated carbon decreases with decreasing assault concentration for gas concentration levels from 50 to 3000 ppm.

Chemically treated adsorbent filters are systems where contaminants are removed from the air through an irreversible reaction between the contaminant and the reagent on the filter material. Chemically treated sorbent systems have been used for many years and, if properly designed, are quite effective (Kelly and Kinkead, 1993). Testing of such filters has shown them to be more efficient for air contaminants present at parts per million (by volume, ppmv).

However, levels of the key toxic and oxidizing pollutants in air are often less than 0.1 ppmv (equals 100 parts per billion by volume, ppbv). Consequently, the previous testing at ppmv levels has not fully established the behavior and effectiveness of chemically treated air purifiers at the ppbv contaminant levels representative of the real world.

Air washers

These have been used primarily for special applications in spacecraft and undersea craft and for humidity control. Additives in the water are used for specific cases, such as bacterial control and

2023687722

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

removal of CO_2 and CO. Air washers can absorb many gases; however, there are no acceptable standards for general ventilation system performance and maintenance is necessary. Inadequately treated water sumps may be "environmental niches" where biomatter can multiply (McNall, 1986).

Humidity control

Humidity control can play an important roll in both the reduction of sources (fungi and bacteria) and in providing comfort. A theoretical study indicates that a desiccant wheel could reduce energy costs and increase comfort for residences (Novosel et al., 1987). Desiccant wheels are effective mainly in a hot and humid climate.

Emerging technologies

This section lists emerging technologies and technologies which are not ordinarily used for commercial building IAQ.

Drum filters are often used in industrial applications to filter fibrous particles. Fibrous particles are different than conventional particles in 6 major characteristics:

1) fibrous particles are shaped differently,
2) they have a high aspect ratio,
3) Fibrous particles tend to be larger, (smokes and most dusts are submicron in size, most process generated fibrous particles are 10 microns and larger),
4) they are usually completely dry,
5) fibrous particles from a process tend to be similar in size,
6) they have fairly smooth surfaces and
7) they are less dense than other industrial dusts.

Pleated dry processed carbon composite (DPCC) adsorbers are based on new carbon technology that reduces overall adsorber weight by as much as 75% without sacrificing service life (Kinkead, 1990). This is a new technology available for the removal of low level gas phase pollutants in the indoor air environment.

Tests have been conducted on two filters with one filter incorporating reagents specifically meant for the removal of formaldehyde; while the other had reagents specific for the removal of sulfur dioxide, nitrogen dioxide and ozone. The results of the test showed that the adsorbers achieve very high removal efficiencies for the target contaminants, far exceeding the efficiencies required by the protocol.

Biofilters are vessels packed with a supporting material through which air (or other gas) passes

2023687723

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

through for cleaning. They have microbes which degrade the undesirable components aerobically (Miller et al. 1993). When a biofilter is working properly, the odorous compounds in the gas stream are oxidized to carbon dioxide, water and some mineral salts (Williams et al., 1992). Williams further notes that, as the odorous compounds are oxidized, adsorptive sites in the biofilters become available for additional odorous compounds in the air stream, thereby self regenerating the filters's odor removal capacity.

Biofiltration is used a lot in the European countries to clean exhaust air from livestock buildings. It has also been used for a long time in waste water treatment plants to reduce the odors that come from treatment operations. Zeisig (1988) showed that odor from a stable was reduced where biofilters were installed. The fact that biofiltration has been successful for odor reduction in livestock buildings is a good reason to try this technology in office and residential buildings. Research work is required to determine the optimal filter size and operating conditions such as the moisture content, relative humidity, pH, temperature and depth of bed to determine a most economical filter.

Building operators need to have answers to the following questions readily available. How often should particle filters be changed? Should pressure drop be considered? How often should EACs be cleaned? What should be done with spent filters? What should be done with collected material from EACs? What should be done with used gas phase filters? Can or should used gas phase filters be recharged? Are used filters hazardous waste or regular commercial waste? How often should gas phase filters be changed? Should operational efficiency be considered? How would it be measured? Should operational efficiency be monitored continuously? When should testing begin? What training and certification do filter operators and other field personnel need?

What is the relationship between the rate activated carbon is loaded to the amount it can hold? Do VOCs migrate from capture sites to other parts of the bed. Typical residence times for air flowing through a bed is less than a tenth of a second. If there exists large numbers of low rate (time) sorption sites in or on activated carbon, gases might be able to go from fast sites to slow sites. This effect would not be observed in experiments currently reviewed but it could be very real in the field.

In duct EACs have the advantage that air flowing off them frequently goes through metal lined duct work for a 15 second trip time or longer. Such duct work could be an effective "filter" of O_3. Currently reviewed research regarding O_3 production has apparatus constructed in a way that eliminates this possible effect. Furthermore, O_3 is a reactive gas which readily degrades in atmosphere into harmless gases. Experiments regarding O_3 production should consider the transit time from the EAC to humans or other vulnerable building occupants in determining true production rates.

Knight et al. (1993) studied a rotary wheel carbon bed. The authors' assumption that all adsorption is completely reversible, probably jeopardized (or invalidated) the results. The model does

2023687724

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

demonstrate how effective it can reduce indoor air concentrations of pollutants to levels below outdoor concentrations. Chung et al. (1993) looked at the efficacy of removing various problem gases from the air in buildings with the solutions used for dehumidification. LiCl was a poor remover of formaldehyde and toluene (15 to 20% removal). Triethylene glycol (TEG) did well removing toluene and 1,1,1 - trichloroethane (100% removal), but did poorly against formaldehyde (about 25% removal). Triethylene glycol was also effective (about 50% removal) at removing CO_2. This should be noted for buildings using triethylene glycol dehumidification and CO_2 based demand ventilation. The TEG will corrupt the meaning of the CO_2 measurement.

Ensor et al. (1988) suggest using the following guidelines in choosing an EAC:

1) use positive (rather than negative) polarity corona,
2) use a two stage design in which the charging and collection functions are separate,
3) use of smooth, round corona wire of the smallest diameter compatible with mechanical strength,
4) use the lowest possible corona current compatible with satisfactory collection efficiency,
5) use of the maximum airflow rate compatible with satisfactory collection efficiency and
6) elimination of stray discharges, such as may occur due to end effects, sharp points, or edges.

IAQ MODELS AND MODELING

Approaches for modeling IAQ and ventilation are of two types: microscopic models and macroscopic models. Macroscopic models involve the macroscopic equations of mass, momentum and energy and are useful for determining flow of air and contaminants from one zone to another within a building. Microscopic models, on the other hand, involve solving the equations governing fluid flow and contaminant transport and are used to determine details of air and contaminant movement within spaces.

These two approaches complement one another. For example, macromodels can provide the necessary boundary conditions for the micromodels. The micromodels, on the other hand, can provide the distribution fields of velocity, temperature and contaminants for the macromodels.

The potential of these models in improving ventilation design and operation is great. However, the potential has not been reached yet; neither of the two approaches can yet be applied to everyday design and operation. For example, computational fluid dynamics (CFD) codes that have been developed can be used to model simple flow systems, but fail to accurately model realistic room flow and air contaminant movement. Recently, a group of experts from "Annex 20" evaluated several different CFD codes, including PHOENICS (low Re k-e model), SIMULAR-AIR (standard buoyancy extended k-e model), WISH3D (standard buoyancy extended k-e model), KAMELON (low Re k-e model), EXACT3

2023687725

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

(standard buoyancy extended k-e model), FLUENT (standard buoyancy k-e model) and EOL3D (standard k-e model). To minimize bias results, a standard test room was defined and both simulations and measurements were conducted at several research laboratories. Major findings were (Whittle and Clancy, 1991);

1) Numerical simulation models predicted well, in general, the overall flow patterns, but quantitative differences between predictions and measurements typically varied by a factor, which were attributed to the weakness in the simulation model and to uncertainties involved in experimental measurements.
2) The specification of boundary conditions (e.g., flow around the diffuser and heater) was found to be critical for obtaining reliable numerical predictions. More detailed measurement data or appropriate models for boundary regions are needed for evaluating and improving CFD model predictions.
3) Further improvement of the turbulence model is needed for improving numerical predictions.

2023687726

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

HVAC INDUSTRY SURVEY

What is the industry thinking and where is it heading? In order to define current practices and the state of the art concerning ventilation technology and indoor air quality, professionals and experts in the field were queried. The survey was organized to complement information available from a literature review and supplement this with common industry knowledge.

SURVEY METHODOLOGY

Five groups were identified as having an influence on IAQ in office buildings. The five groups of respondents were identified through an idealistic technological/product/information flow within the HVAC industry. Figure 8 illustrates this process.

Group name	Activities description
Researchers	Development of technologies to support future industry development Laboratory and field products and systems testing Scientific basis development for industry standards and regulations
Manufacturers	Provide R&D Develop market and product information Production Provide training of the sales personnel and customers (consultants, designers, contractors, building managers and owners)
Designers	Design systems and specify their elements Adapt technology within cost and facility limits
Contractors	Construct and balance systems
Managers	Operate and maintain systems Troubleshoot and adjust

Figure 8. Technological/product/information flow within the HVAC industry.

The survey of 975 professionals included: 100 researchers, 250 manufacturers, 300 designers, 125 contractors and 200 building owners and managers. We received 252 responses which represents 26% of the number of people surveyed.

2023687727

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Contractors showed little interest in participating in the survey, believing that IAQ problems were a result of design, maintenance and ownership and not construction. The eight contractors that did respond had engineering and design backgrounds; therefore, their responses were incorporated into the designer's group.

The surveys were provided in two phases: ten individuals from each subject group were contacted to evaluate its content. The surveys were adjusted according to their comments and mailed out to 975 professionals.

ISSUES ADDRESSED

The surveys were outlined to extract the variance of importance each subject group had toward IAQ. Their perspective of factors influencing IAQ and major causes of poor IAQ were requested through a series of questions. Information was solicited through the whole scope of the industry: research and development, design and installation, and operation and maintenance. Surveys also contained questions about system failures, and what is being done and should be done to detect and mitigate IAQ problems or ventilation system failures within each stage of the industry process.

All of the surveys have some common themes, with questions phrased appropriately for its respective subject group. General questions are first asked, followed by more specific questions. Some questions are unique to each subject group. Through contact with consultants and designers, current practices in application of ventilation technology were assessed by evaluating how systems are selected, designed, and constructed. Researchers were surveyed to identify emerging technologies and current research areas dealing with IAQ. Managers and owners outlined how systems are operated, maintained and their perceived success at maintaining a healthy IAQ. Equipment manufacturers lead to an understanding of new product development.

FINDINGS

All respondents rated the importance of IAQ as an issue with 1 being not an issue and 5 representing a big issue (Figure 9). All four groups believe IAQ is an important issue. On average, over 77% of the respondents rated IAQ as a 4 or 5. Equipment manufacturers, researchers and building managers all have similar distributions for rating the importance of IAQ as an issue (Figure 9). Only designers differ in distribution; 28% of the designers believe IAQ is a big issue, rating it as a 5, while 40% of the other three groups rated IAQ as a 5. Designers were the only group that had some respondents rank IAQ as not an issue at all, rating it at 1. Perhaps the overriding concern among most of those surveyed was the lack of team involvement in the planning, design, construction, management, and ownership of the facility.

2023687728

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

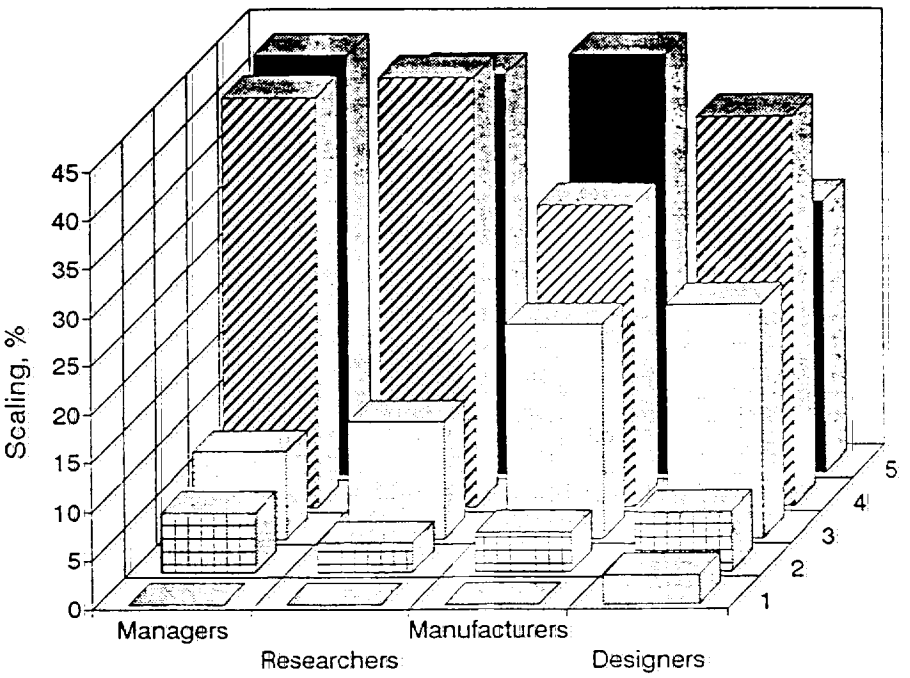


Figure 9. How the four subject groups scaled IAQ as an issue.

Researchers

With all the publicity concerning the "sick building syndrome" (SBS), researchers were asked if they personally knew of a "sick" building. Sixty-six percent of the researchers who responded said they did. Common symptoms mentioned by the occupants of these buildings included headaches, nausea, dizziness, skin rashes, and immune reactions. The occupants also complained of stuffiness in the rooms, bad odors, fungal growth, lack of temperature control in some areas (too cold and too warm), and excess moisture content in the room.

Some of the reasons cited for these problems included poor air distribution within the room, insufficient outdoor air brought to the interior spaces, inadequate temperature and humidity control, poor operation and maintenance, improper location of outdoor air intakes/contaminated intakes, improper duct balancing, overcrowding, no operating windows, and contamination of the AC system.

System design

When asked what the most common design mistake was, the most frequent answers included inadequate ventilation, improper air distribution, and poor accessibility for maintenance. Other mistakes included improper placement of air intakes and exhausts, assuming there will be no changes in occupancy

2023687729

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

or pollution sources and assuming that building controls work.

The most common design constraints cited by the researchers were cost and ventilation rate. Other important constraints included energy conservation considerations and a lack of simple, clear and practical guidelines for operations and maintenance.

Industry weakness

The researchers were asked what they perceived as the greatest weaknesses within the HVAC industry as related to the areas of equipment and indoor air quality. The answers to these questions pointed out deficiencies and needs in the industry.

Equipment needs mentioned by researchers included the following: improved controls, a uniform protocol for control languages, humidificators that eliminate microbe growth, sensors for detecting the concentration and movement of contaminants, and improved duct insulation that doesn't emit fibers and harbor microbe growth.

Deficiencies of HVAC equipment mentioned by the researchers were HVAC component incompatibility, poor system/component reliability, the equipment is not designed for easy maintenance, the motors for fans and pumps create excessive noise, and damper technology is inadequate.

The current deficiencies in IAQ technology according to the researchers are partially due to a lack of knowledge. These include a lack of understanding of air distribution patterns, the effects of various contaminants at varying concentration levels over time, an inability to predict concentration levels based on velocity and source strength information, and a lack of performance knowledge.

Another part of the IAQ problem is due to designers and building managers/owners having little or no knowledge of IAQ theory and parameters. This situation is created partially because there are no well defined criteria outlining acceptable IAQ. Designers are hampered because there exists no commonly known systematic approach that details how to design for good IAQ. An integrated design tool which takes into account both energy conservation and IAQ is also needed. Many building managers are not aware of the maintenance and operational issues involved in obtaining suitable environmental quality. Even if the managers are properly trained, some of these problems stem from improper installation and lack of proper commissioning. While some codes already exist, some researchers felt that they place too much reliance on mandating high ventilating rates, and do not guarantee good IAQ.

IAQ deficiencies are also related to deficiencies in equipment. Respondents stated that effective and affordable sensors and sensing criteria were needed for detecting moisture in walls and floor systems,

2023687730

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

and measuring air quality (CO_2, VOC). Improvements in filters and duct lining are also needed.

When researchers were asked what other important deficiencies existed in the HVAC industry, the following items were mentioned: HVAC specialists and industrial hygienists operate independently without knowledge the other group exists, and resistance to change within the industry.

Contaminant sources and sinks play a major role in indoor air quality. In review of this, researchers were asked where further evaluation needed to be done. Sources and sinks mentioned were as follows: volatile organic substances and particulate, biological contaminants, pathogens in inhaled air, aerosols, formaldehyde, tobacco smoke, radon, offgasing of construction and furnishing materials, indoor pesticides, cleansers and disinfectants, building exhaust air reintrainment, heat and odors from office machines, plants, filter blow through, H & AC equipment (including cooling coil drain pans), ducts, porous insulation, and adsorption/desorption from surfaces and materials.

Research

Although further IAQ improvements need to be made, HVAC research has made direct contributions to improving IAQ. The most commonly mentioned contributions include increasing the general awareness of IAQ through education, identifying the issues (like SBS) and possible solutions, and establishing ventilation standards. Other contributions include a better understanding of air distribution, ventilation effectiveness, health implications, sources and sinks, and the importance of commissioning. Further research advances in computer control technology, heat recovery, and air filtering systems also benefitted IAQ.

While some survey respondents felt that HVAC research dominated IAQ improvements, others felt that the HVAC industry was just beginning to perform original research and had previously been relying on the American Conference of Governmental Industrial Hygienists (ACGIH) data.

Survey participants were asked what direction HVAC research should take in the immediate future. The responses were quite varied and reflected the need for further research in a number of areas. It was clear from the survey that additional information is still needed in the areas of cold air distribution, mass transport, material emissions, sources of pollution, and the effects of building environment contaminants on occupant discomfort and health.

Equipment for which respondents thought further research was needed included inexpensive CO_2 and VOC sensors, air-to-air heat exchangers/heat recovery equipment, carbon and particulate filters, and integrated ventilation and H & AC systems for residential purposes.

2023687731

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Model development for simulation purposes was mentioned as an important direction for future research. Particular models mentioned were an indoor contaminant migration model, a combination CFD and multizone model, and a system performance model.

Other directions for further research development include control methods based on IAQ parameters and humidity, airflow measurement techniques, control of contaminant emissions from inside HVAC equipment, energy conscious ventilation methods, validation of ASHRAE Standard 62-1989, floor to ceiling air exchange, and integration of solar energy with HVAC.

Some researchers were also interested in determining ventilation requirements in terms of CO_2 in ppm rather than l/s per person of fresh air, and finding out whether CO_2 or humidity monitoring correlate with other contaminants.

In an effort to identify what new or emerging technologies could offer improved IAQ, researchers were asked for their input. Many respondents mentioned CFD modeling, sensors capable of measuring IAQ parameters (such as low velocity flow rates and concentration of pollutant gases), and various control systems such as distributed direct digital control, DDC, and fuzzy logic. The integration of these sensors with control algorithms was viewed as having great potential in improving IAQ. Other emerging technologies in equipment that might offer improved IAQ in the future include: heat recovery systems, duct cleaning systems, air filters, light pipes, desiccant systems that can drop humidity below the microbe growth zone, chilled ceilings, and variable area diffusers.

Other technologies that could improve IAQ include cold air distribution, characterization of source emissions and their relation with IAQ models, low emitting materials, improved tracer gas measurement techniques, properly designed displacement ventilation systems, source control of VOC's and microbes in construction materials.

Designers

The HVAC system designers subject group included architects, HVAC engineers, mechanical designers, HVAC diagnosis professions, balancers, and the participating contractors with design experience. Those participating had been working in the HVAC industry for an average of twenty years, with most having engineering training.

System design

The group was asked to outline the types of systems and their performance as related to IAQ and thermal comfort. Figure 10 shows the percentages of different HVAC systems that have been designed

2023687732

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

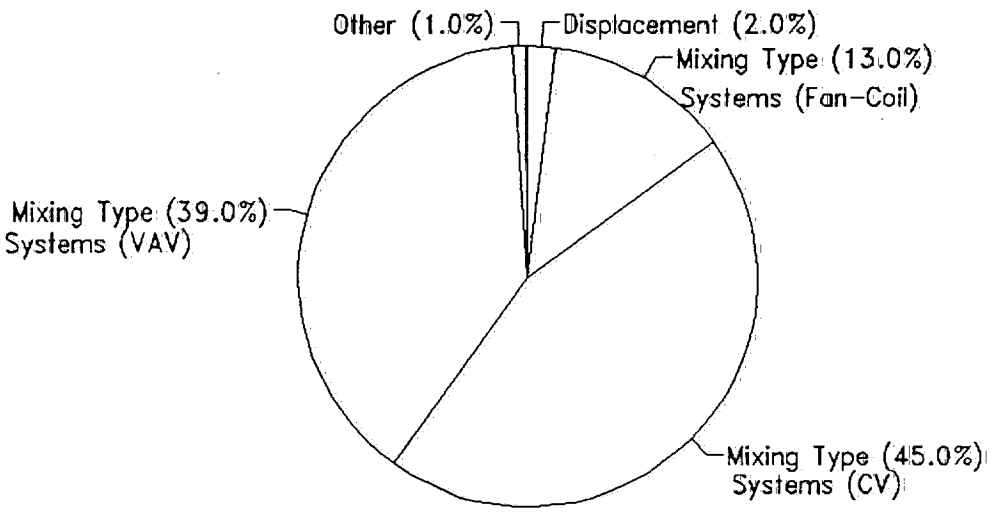


Figure 10. Percentages of systems designed in the last 15 years.

in the last 15 years. Ninety-seven percent of the systems designed were mixing type systems. Displacement ventilation was represented by two percent of the designs; however, those designers that use displacement ventilation usually designed more than half of their designs this way. The variable air volume systems were subdivided into three groups as follows: with return fan, single fan and other. Fifty-five percent of the VAV systems were designed with a return fan, while thirty-five percent were designed with a single fan. The constant air volume systems represented forty-five percent of the total designs (see Figure 10) and were divided into four groups. The constant volume systems and their respective percentages are as follows: single zone, 71%; multizone, 20%; dual duct, 7%; and other, 2%.

The performances of the systems designed are shown in Figure 13. The thermal performance from the constant volume systems and displacement ventilation was ranked higher than the thermal performance of the variable air volume systems. The fan-coil system received the lowest ranking. Differences in IAQ performance was not as significant between and within systems types. The variable air volume with return fan received the highest ranking for IAQ performance, while the constant volume

2023687733

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

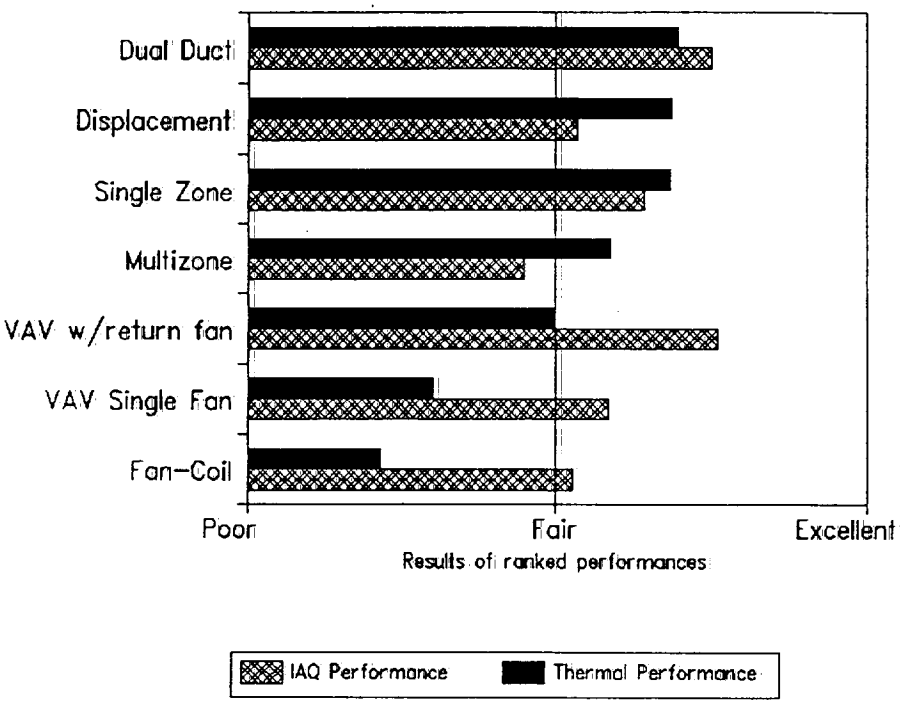


Figure 11. IAQ and thermal performance of systems designed in the last 15 years.

multizone system was ranked as the poorest IAQ performance system.

Designers were asked how often they were able to design and specify an air supply and distribution system and its control to achieve: good thermal comfort, good humidity control, good room air circulation, good air filtering/cleaning, good outside air ventilation, low maintenance costs, an easily maintained system, and good energy conservation. The results for control and design of different system constraints are shown in Figure 12. Thermal comfort and room air circulation are the most easy to design and control, while humidity and maintenance costs are the most difficult to design and control. Eighty-eight percent of the time designers are able to frequently design for thermal comfort; however, they can freqently design for humidity control thirty-eight percent of the time.

The quality of a design is influenced from many external and indirect factors. Several factors that influence the HVAC system design and its resulting IAQ were listed and ranked. Designers were asked to define how often the factor influenced IAQ; never, seldom, occasionally, and often. The rated results

2023687734

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

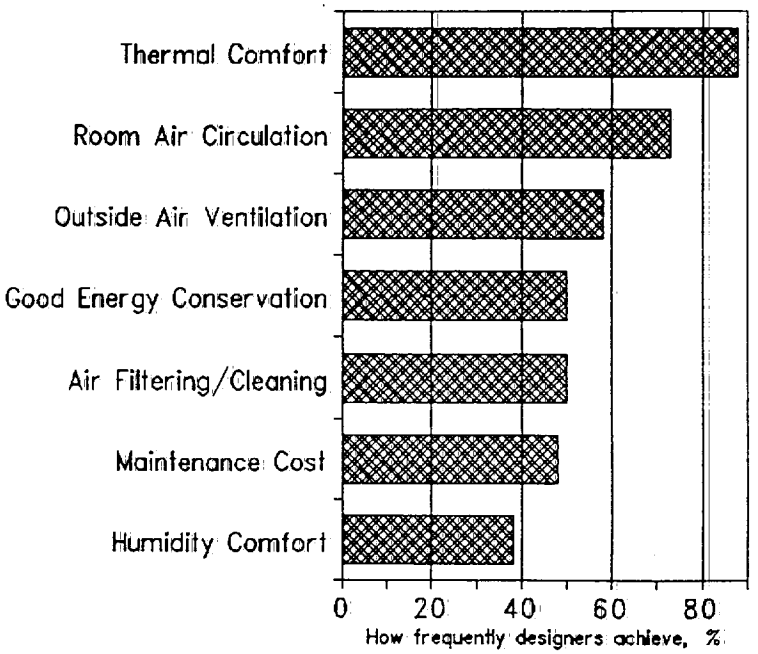


Figure 12. How frequently designers are able to design and specify air supply, distribution and its control.

from the factors influence are shown in Figure 13. Maintenance and operation most often caused an indoor air quality problem and incorrect construction and performance of equipment and incorrect construction seldom did.

Designers were also asked how often listed factors impacted negatively on the air supply and distribution of systems and controls they designed and specified (see Figure 14). Architect, engineer, and design equipment costs, and owner standards were ranked as most often contributing negatively to the quality of air supply and distribution. Standards and design tools were seldom negative impacts on the quality of the air supply and distribution system.

Designers were asked what types of design tools, information, standards, and codes are needed to improve their ability to design HVAC systems and ensure good IAQ and building systems. The concern for regulation was easily recognized in their responses. Comments were focused into four different areas general information deficiencies, standard revisions, education, and design tools. To properly design

2023687735

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

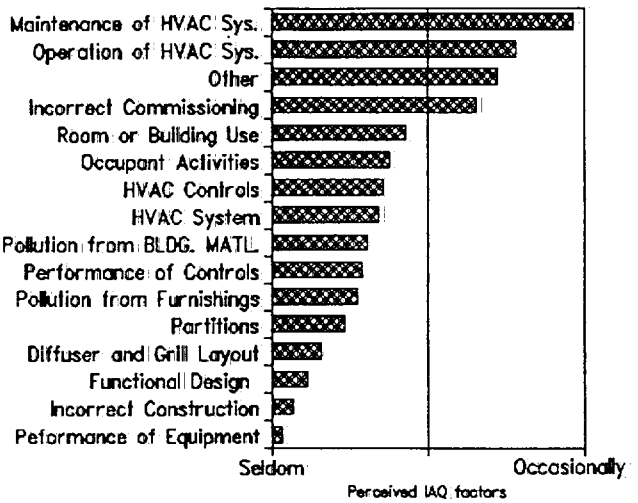


Figure 13. Factors that cause indoor air quality problems.

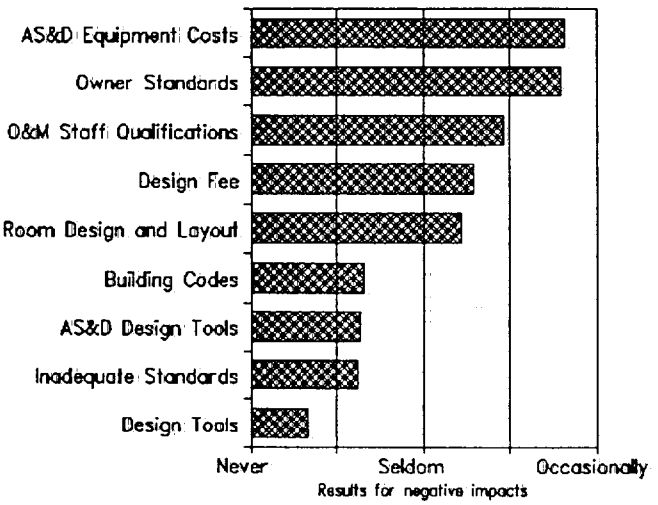


Figure 14. Results for factors that impact negatively on the air supply, distribution systems and controls.

systems to address current IAQ issues more information and a better understanding is needed in dealing

2023687736

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

with contaminant sources and their effects from reasonable levels of exposure.

Industry weakness

Almost all participants addressed the need for a revolution in existing codes and standards. Many mentioned the need for better information on effects from minimum levels of indoor contaminants to be incorporated into existing standards. Some said existing standards and codes are too weak and often ignored. Standards should be stronger to support a designer's position when negotiating with the owners and architects. There is a need for mandatory minimum ventilation standards with enforcement. Some believe the existing standards are sufficient if they are only applied. Standards on indoor pollutants and offgassing are desired. Standards also need to include minimum setback distances for air intakes from loading docks. Guidelines on operation and maintenance need to be incorporated into a standard form. Some suggest CO_2 levels should be introduced as an alternate way to measure ventilation performance. Several suggestions contradict one another, such as, more lenient emission standards and stricter emission standards, as well as more outside air and less outside air. Many agree on required balancing procedures and a commissioning process. ASHRAE 62-1989 was criticized several times for being uninterpretable and confusing. It also fails to mandate system balancing. They believe it will be widely adopted by municipalities before it has been organized into a code format.

Existing tools are adequate for educated design professionals; however, building owners and managers need more education regarding requirements of designing and operating equipment for good IAQ. IAQ education for all parties involved was a focus of several participants. There was a need expressed for educational tools to help operators and maintenance understand better their systems. One system tool that was suggested was to develop a HVAC design program for conference rooms. Some designers said we have too many tools and guidelines to be effective as it is. We need to just become more conscientious designers and owners and address the new problems of low operation and maintenance skill levels and new construction techniques into our old talents. It's a matter of using common sense and good engineering principles.

Research

What HVAC equipment needs further development to improve our ability to control and design good IAQ? Several suggestions were made. New equipment techniques are usually limited by costs. Many designers see many uses for equipment, but since systems are usually constrained by costs, sacrifices in equipment are usually the first. In general, flow measurement devices, new controls and control techniques, and better education on existing equipment is needed.

There were suggestions for a flow measuring device with enough turndown and reliability to make

2023687737

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

outside air monitoring practical. Air flow monitoring was mentioned by several participants for a variety of applications. Some suggest work on outdoor air cleaning devices when outdoor air is very poor, such as near major highways and near heavy industrial sites. Controls need to be improved to handle minimum levels and introduction of outside air. Direct controls were mentioned for CO_2 and humidity as opposed to indirect controls now in use. Several participants mention the need for a crude IAQ sensor for multi-contaminant measurement or detection. Filter systems need feedback to identify indoor air pollutants. Many believe there is an absence in creative filtering techniques, but on the other hand many mention their reluctance to incorporate new technologies on proven techniques. The more complicated equipment becomes, the more problems occur in training, troubleshooting and operating the equipment.

Education and training is needed to ensure that operators and managers can maintain the systems as they are designed. One participant summarized it well for many of the participants. He wrote, "Basically, everything needed is out there; the problem is inadequate maintenance and understanding by the end user."

Designers were asked what changes will have the greatest impact on the immediate future in the HVAC industry. It was almost a consensus; everyone mentioned some aspect of regulations and public perception. It is believed by some that technical issues such as equipment, emerging technologies and system designs will not have a major impact due to the growing public interest in IAQ. Regulations and standards driven by public perception will become the major issue. Again, education for the public, owners and managers will help shape public perception into a positive contribution to the industry and not just legislative and litigation battles.

Managers

The managers subject group had an average of 15 years experience of managing HVAC system related operations. Each manager was responsible for an average 1.25 million square feet. Ninety-nine percent of their systems were mixing type ventilation systems. Figure 15 shows the percentages of each type of system they managed. The largest percentage of any of the systems was constant volume systems, at forty-six percent followed by variable air volume systems at forty-two percent. Displacement ventilation was less than one percent of the systems managed and was included into the other category.

A variety of management techniques and trouble shooting procedures were outlined by the group. When asked how often the managers check the system and room ventilation, responses varied from continuously to never and not sure. On the average, total ventilation rates are checked every three and a half years, and individual room rates were checked every five and a half years. Managers estimated that sixteen percent of their total building related complaints were related to IAQ. Temperature was the most often reported IAQ and comfort complaint at almost sixty percent (Figure 16). Dust was the least

2023687738

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

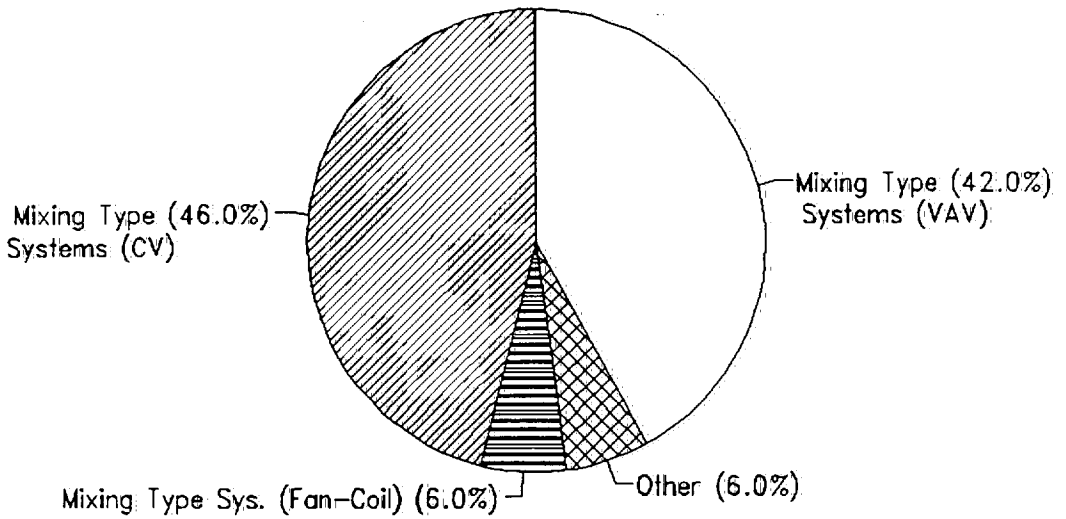


Figure 15. HVAC system types managed by the building manager survey participants.

reported complaint. Not listed on the survey but was reported by the subjects in the "other" category was odors. More than half of the "other" category was represented by odors which was not listed in the survey choices.

Managers were asked what adjustments/modifications they were able to make on the HVAC systems for improving the IAQ and comfort (Figure 17). Temperature and filter replacement were both adjustments that could be made on almost ninety percent of the buildings managed. While system balancing and humidity adjustments were only possible in sixty percent of the buildings.

Equipment Manufacturers

In an effort to better understand how equipment manufacturers operate, manufacturers of all types of HVAC-related equipment were surveyed. The respondents from the equipment manufacturers group had been working in the HVAC industry on average for twenty-one years.

2023687739

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

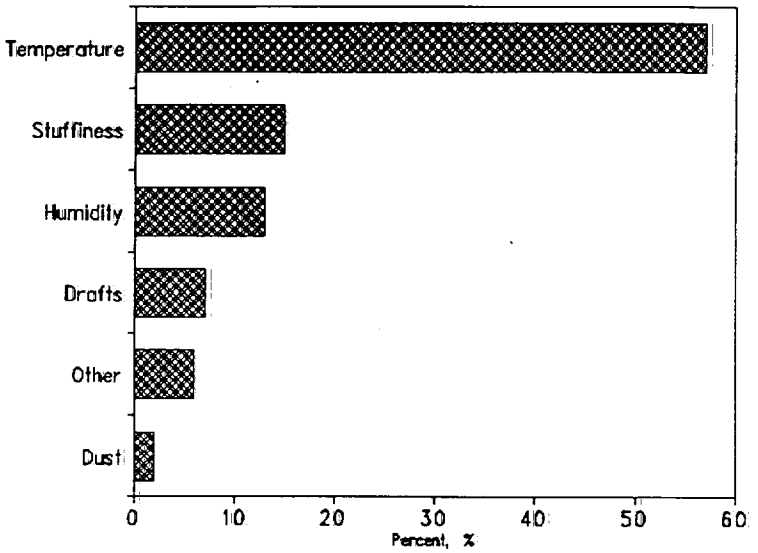


Figure 16. Percentage of IAQ and comfort complaints registered by managers.

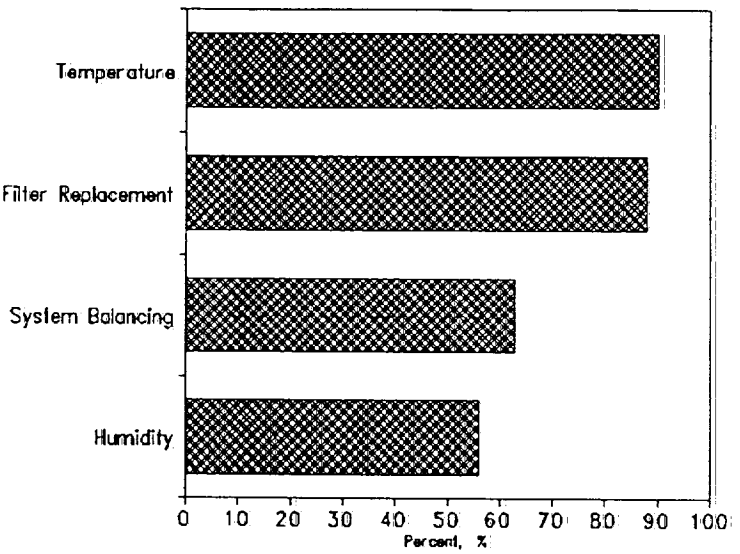


Figure 17. Adjustments and modifications managers are able to make on their systems.

2023687740

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

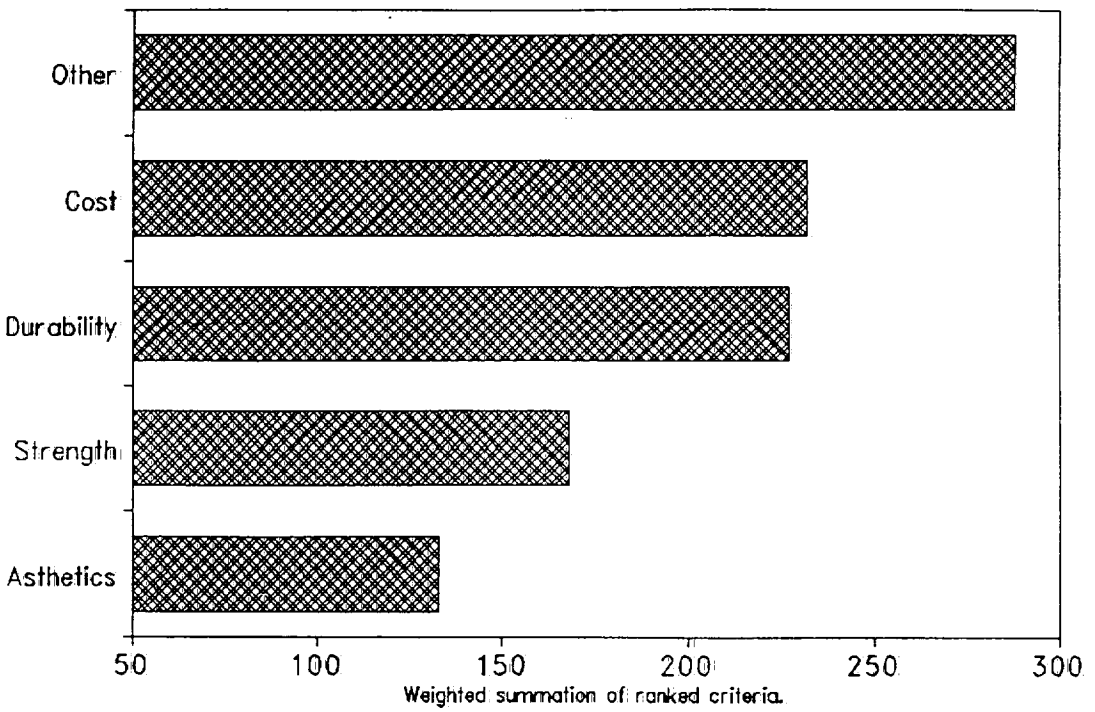


Figure 18. Results of ranked equipment criteria when designing new products.

System design

Manufacturers were asked to rank in order of preference the factors which they considered most important when designing, manufacturing, and marketing their products. Figure 18 summarizes these results and it is interesting to note that the "other" category (written in) scored ahead of the four listed criteria of cost, durability, strength and aesthetics. The "other" category is broken down into 11 separate components in Figure 19. Each component had to be mentioned at least twice in the survey. In the overall ranking, the most important factor was cost, followed by durability, strength, aesthetics, performance, and the rest of the components on Figure 19.

In a related issue, these manufacturers were asked how long it took their company to develop a new product. The average development time cited was 1.4 years. It was also of interest to determine if product design and development focused on individual component performance, system performance, or both. Figure 20 shows that the majority of equipment manufacturers focus on the overall system performance.

2023687741

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

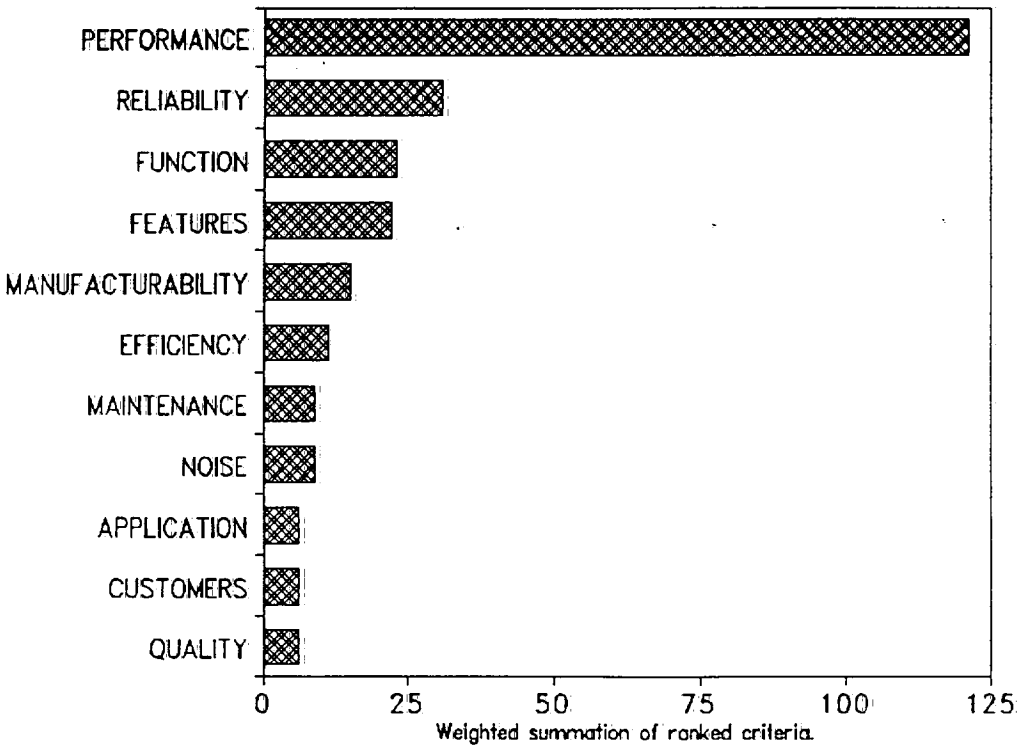


Figure 19. Results from "other" design criteria not listed in survey.

Industry weakness

The ability of manufacturers to learn about and respond to new trends can greatly influence the future of the HVAC industry. The survey respondents were asked how they learn about new trends. The results are shown in Figure 21. When asked how long it took the HVAC industry to respond to these new trends and technologies, 21.4 months was the average answer given.

Once a product is developed by an equipment manufacturer, feedback is valuable for assessing the product's strengths and weaknesses. Figure 22 shows the respective percentages of survey respondents who always, often, rarely, or never received feedback on their product performance. To get an idea where some of this feedback may come from, equipment manufacturers were asked if they worked closely with and exchanged information with the following groups: architects, engineers, building managers, industrial hygienists, building owners, and contractors. Figure 23 shows the percentage of equipment manufacturers who exchange information with each respective group. It is interesting to note that engineers and contractors are the most common contacts, while these are the groups least concerned with

2023687742

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

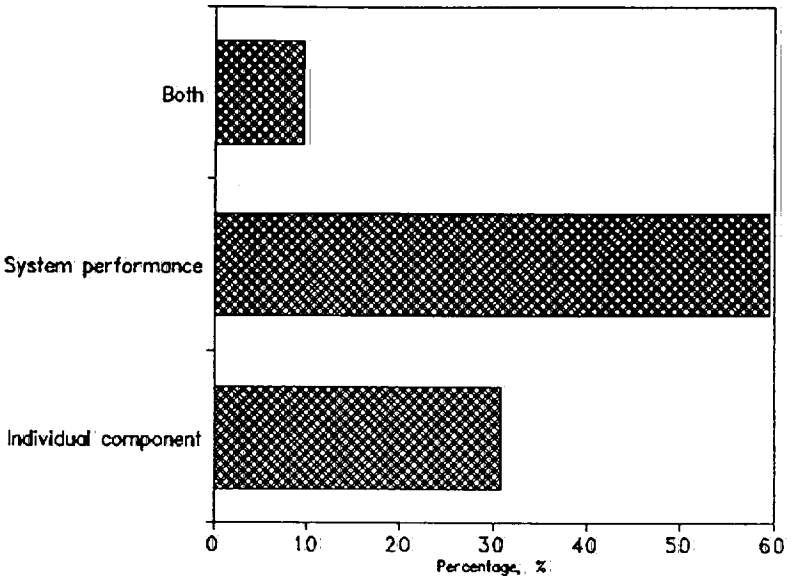


Figure 20. What manufacturers focus on in product design and development.

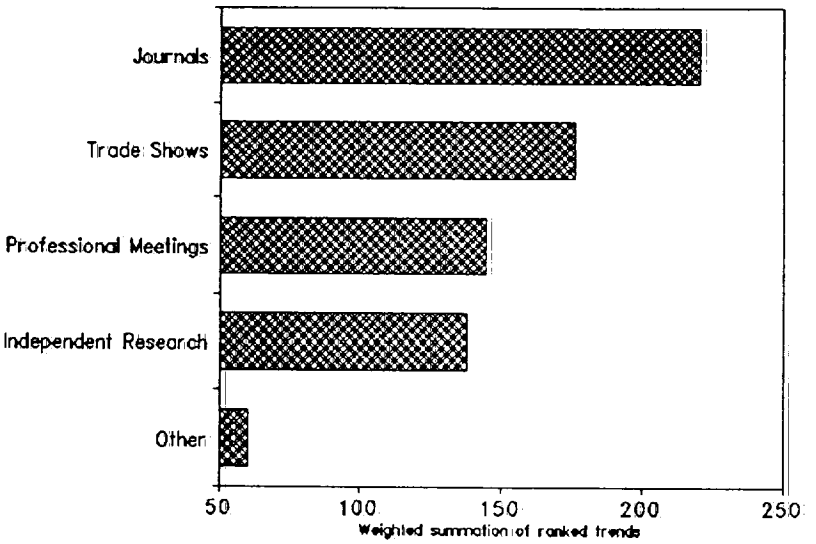


Figure 21. Results of ranked order of preference, where new trends are identified.

2023687743

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

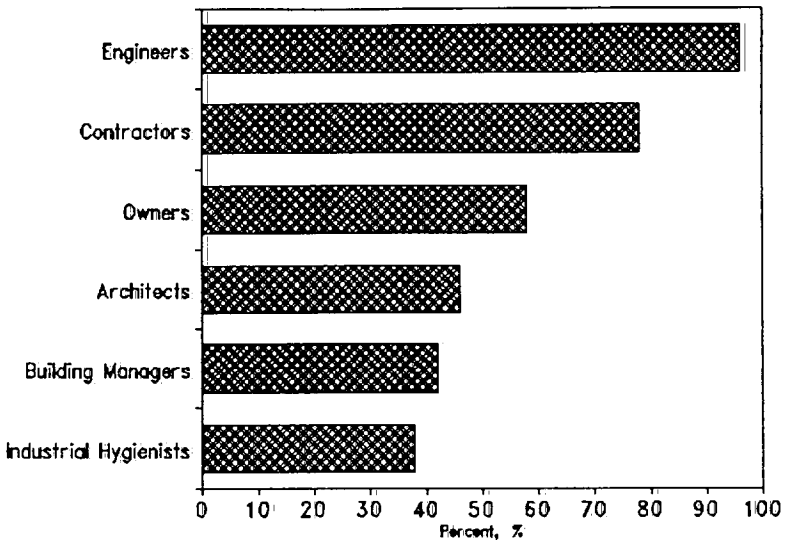


Figure 22. Who manufacturers exchange information with, when designing products.

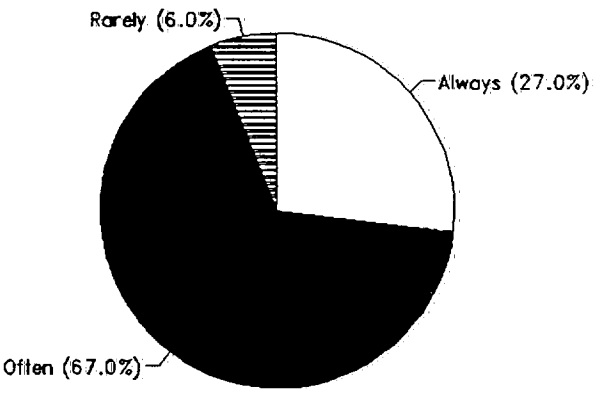


Figure 23. Percentages of how often manufacturers receive equipment feedback.

2023687744

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

IAQ issues, according to our surveys.

Research

In an effort to improve the research contribution to the HVAC industry, respondents were asked how researchers in universities and public laboratories should change to better benefit the industry. There was overwhelming agreement on a number of points. One of these points was that researchers should work more closely with industry leaders to keep up with the current technology being applied. Many respondents felt that current public research lags behind developments in the industry and could significantly be improved by joint ventures. It was noted that some recent successful developments in this area involve a consortium of companies funding a research project of mutual interest with a university.

Another point was that, while research laboratories are valuable for testing ideas, many times the solutions obtained there are not practical to implement. Many respondents recommended that realistic research be carried out in actual field conditions. This would help the researchers to understand what the real problems and applications are in the field and whether solutions are financially feasible. Performing case studies that evaluate field installations and overall system performance on the basis of cost, efficiency, reliability, and maintenance would also be valuable.

The equipment manufacturers echoed other survey group results by requesting that researchers determine the impact and effects of poor air quality, then define IAQ issues and requirements. Specific research needs mentioned include further development of electronic air cleaners, alternate refrigerants, lubricants, and desiccants. Other points mentioned were to focus attention on chemical absorbants to determine absorption rates by grade and airflow ppm concentrations.

The last question on the equipment manufacturers survey asked what changes will have the greatest impact on the immediate future of the HVAC industry. Almost 80% of the respondents mentioned regulations of one form or another (CFC's, air quality, PELS, etc.) as having a huge impact. Other commonly mentioned changes included energy costs/conservation, public perception, legal ramifications, and emerging technologies that centered around IAQ measurement and control.

WORKSHOP COMMENTS

During the workshop, held from September 14-16, 1993, specialty groups were organized to help define current state-of-the-art and identify major issues and concerns in ventilation and indoor air quality specific to their group. Workshop participants were divided into seven industry groups: researchers, designers, equipment manufacturers, commissioners/balancers, operation/maintenance, owners/managers and utilities. Each participant was placed in the group that best represented his or her background and varied experiences. Group members evaluated current and future roles in context of ventilation/IAQ and

2023687745

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

identified the most important knowledge deficiencies/challenges.

Researchers

Researchers viewed their role as having a dual purpose. They benefit the industry by meeting the need for research to gain understanding and educating the industry to see that the research is implemented. As our understanding of IAQ grows and methods for its control improve, education must occur at all levels for the new technological advances to be adopted.

Researchers saw several areas of improvement to satisfy their role. Researchers believe they need a more multi-disciplinary approach. More emphasis also is needed on technology transfer to insure the commercialization of research. Industry would benefit from continuing education, joint projects, training of technicians, and laboratory and field studies. Researchers would benefit by obtaining needed financial support and advice.

Researchers identified the following ten deficiencies to be of greatest importance;

1) Criteria for acceptable indoor air quality.
2) Relationships among HVAC system design and IAQ, thermal comfort, health and cost.
3) Methods to control IAQ sources.
4) Economic analysis (life cycle cost analysis, optimum first cost, maintenance cost etc.).
5) Environmental sensors and practical methods/techniques to measure and control thermal comfort and IAQ parameters.
6) Information on air cleaners concerning impacts on overall HVAC system performance and the factors that affect performance.
7) Acceptance of commissioning is important.
8) Component system reliability.
9) Operation and maintenance training and self-diagnosing systems.
10) Information on the quantity of outside air is actually delivered to the occupied zone.

Designers

Designers viewed their role as having responsibility to design systems and oversee their implementation. Architects and engineers should be the primary participants for interior environmental quality. They see themselves as needing to improve communication, coordination and education among disciplines. Their group has a conflict among current good practice, codes and the latest ASHRAE standards. Designers have the responsibility to generate change in the process and products; however, the legal responsibility falls upon this group more than any other group and this limits flexibility and creative approaches. Designers outlined areas in which their specialty group could improve. They can design

2023687746

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

better systems than dictated by codes and/or building owners. They also can design to latest discoveries and standards and promote advances. Designers need to be involved in the development of codes and standards. Successful implementation of design intent needs to be assured by the design professional. They recognize a need to educate owners and the general public on IAQ issues. They can assist by informing the owner and operators of the building on the performance factors and limitations of the building. The idea is to help building owners develop a "Green" building program with annual building check ups.

Designers identified the following ten deficiencies;

1) For design purposes, fundamental information about sources needs to be developed.
2) Assessment of ventilation effectiveness of various systems (especially VAV) and how they handle pollution loads.
3) Evaluation of pollutants effects on building inhabitants (exposure, dose).
4) Quantification of the economic effect.
5) Determination of whether filtration recirculated air is a better design solution than bringing in large amounts of outdoor air (from both an energy conservation and IAQ viewpoint).
6) Integration of commissioning into the building process.
7) Considerations of operations and maintenance during the design.
8) Dynamic response information on the space and the system to changing interior environments.
9) Definition of acceptable indoor air quality (IAQ standard).
10) Assessment of the other factors that affect occupant impressions concerning total environmental quality.

Utilities

Ideally, the role of the utility group is to educate architects and engineers and end users (electric consumers) on how to meet indoor air quality rates while minimizing energy bills. Utilities can benefit IAQ through product testing and the reporting of these tests to end users. Utilities see that some of the policies utilities make indirectly influence IAQ through rate structures and programs.

Utilities can encourage mutually beneficial programs and rates to decrease kW consumption and consumer energy costs. These changes should promote energy conservation and IAQ issues simultaneously. Where possible, the utility industry should evaluate the impact of its program on IAQ. IAQ should be the driver and then the utilities should help evaluate and reduce the energy impact of these implementations.

2023687747

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Utilities identified the following ten deficiencies;

1) Usable definitions and means of measuring ventilation effectiveness.
2) Information on how much outside air is delivered to the occupied zone.
3) Information quantifying how poor IAQ conditions affect productivity and health costs.
4) Definition of IAQ for standards and guidelines.
5) Knowledge of when and why commissioning and trouble shooting occur for buildings.
6) Control techniques for ventilation.
7) Evaluation of the potential of HVAC systems to serve as an IAQ pollution contaminant source and contaminant pathway.
8) Sensor development for IAQ should be expanded beyond CO_2 sensors.
9) Assessment of the impact of IAQ dissatisfaction upon worker productivity.
10) Standards should be adopted into codes and recommended for good practice.

Equipment Manufacturers

Equipment manufacturers can work to make IAQ a greater priority along with energy management by increasing the maintainability of equipment, redefining the role of air cleaning and broaden it from system air cleaning purposes to IAQ purposes, integrating HVAC equipment into systems that are controlled using better sensors and strategies, preparing application guidelines for our equipment, improving application guidelines to educate our customers and exploring creative solutions like cold air distribution systems.

Equipment manufacturers identified the following ten deficiencies;

1) Filter performance criteria for gases, microbes and particulates. In addition, application guidelines that expand on 62-1989.
2) Information on quantity and quality of the air delivered to the occupied zone.
3) A building commissioning criteria and ongoing certification program to maintain IAQ during equipment life.
4) Practical methods to monitor thermal comfort and IAQ parameters.
5) The impact of thermal comfort parameters (temp, RH, vel.) on overall IAQ.
6) Sensors and performance parameters for O & M purposes.
7) Responsibility for IAQ integrated into the building package to the extent of having assignable and verifiable responsibility.
8) Design coordination between the architect and the engineer throughout the project.
9) Air handling unit leakage ratings.
10) To improve decision making, a method to measure risk factors in design, operation and building ownership.

2023687748

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Owners and Managers

Owners and managers agreed that building owners and managers could improve in four general areas which would significantly affect indoor air quality. Comments ranged from global issues such as budgeting, team building/communication during construction planning and administration phases to micro-level issues such as specific maintenance practices. Indoor air quality is dependant on a series of interlinked actions by owners and managers from project inception through the current date. Indoor air quality should be addressed as a primary concern from initial project programming stages through current operation and maintenance activities, including self inspection, continuous education/training and third party quality assurance consultation activities.

Effective project planning, construction and commissioning of the "Base Building" and its systems are needed. Problems caused by least cost engineering, construction, commissioning, operation and maintenance should be avoided. The HVAC system should be configured to the requirements of the occupant groups prior to occupancy. Emphasis should be placed on the IAQ aspects of buildings operation and maintenance procedures. Property managers should periodically review their buildings with respect to IAQ.

Owners and managers identified the following nine deficiencies:

1) A credible, effective score sheet for building/system/space IAQ evaluation with limits and diagnostics.
2) Air quality standards established through research.
3) Furnishing and finish emissivity standards.
4) Ventilation effectiveness studies to determine whether or not ventilation air is provided reliably to all occupied spaces.
5) Comprehensive IAQ questionnaires/examinations that give a more realistic picture of the indoor air environment.
6) Development of guidelines/standards for different end users.
7) Comparative performance data for different system types to help the owner/designer team provide designs which avoid inappropriate systems and/or design.
8) Case studies compiled to provide building owners and managers data for quantifying the amount of operating capital that could be reasonably set aside for an effective, ongoing maintenance program.
9) Retrofit guidelines that address ventilation, system modifications and material limits.

Commissioners and Balancers

Commissioners, balancers and trouble shooters view their role as the critical link between the

2023687749

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

design and operation. Too often money is not set aside during the construction of a new system to commission properly. "Commissioning do-it!" Commissioning should be a part of the complete HVAC design, construction and operation process. To accomplish this, owners and operators must be educated on the benefits of this practice and the importance of IAQ. All parties must understand that the commissioning process is an ongoing process and can be implemented into the daily activity. Janitorial duty is one daily part of the maintenance portion of the commissioning process; therefore, the lack of cleaning is often a source of IAQ problems. Commissioners, balancers and trouble shooters see a need for the training of operation and maintenance people.

Commissioners, balancers and trouble shooters identified the following ten deficiencies;

1) "Acceptable IAQ" defined and explained.
2) HVAC system designs improved to reduce the possibility that the system itself is a source for contaminants.
3) Information on the ability of the HVAC systems (field assembled and packaged systems) to meet the need of acceptable IAQ under changing atmospheric/occupancy conditions.
4) Determination of whether combinations of pollutants in very low concentrations have a synergistic effect, and if so, whether this can be anticipated with any degree of certainty.
5) Method identified to quantify how poor IAQ conditions affect worker productivity and health costs.
6) Identification of important sources and means of controlling and managing emission.
7) Practical methods/techniques to measure IAQ parameters.
8) Evaluation of factors that affect the performance of system indoor air cleaners.
9) Usable definitions of ventilation effectiveness.
10) The relationships among service scheduling and space use classification, system type and component type.

Operation and Maintenance

Operation and maintenance group members did not outline their roles or determine how they can change to improve the IAQ of the buildings they maintain; however, they did identify the following five deficiencies;

1) Design flexible systems that can accommodate changes in occupancy and sources.
2) Determine correlations among specific IAQ problems and HVAC deficiencies.
3) Evaluate feasible measurement techniques for field measurement.
4) Determine optimum frequency for HVAC inspection servicing.
5) Identify and develop HVAC monitoring sensors for continuous balancing.

2023687750

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

REFERENCES

ACGIH. 1989. Guidelines for the assessment of bioaerosols in the indoor environment. American Conference of Governmental Industrial Hygienists. Cincinnati, OH. 45211-4438.

ACGIH. 1992. Industrial Ventilation: A manual of recommended practice. 2nd ed. American Conference of Governmental Industrial Hygenists. Cincinnati, OH. 45211-4438.

AIVC. 1991. A guide to contaminant removal effectiveness. AIVC Tech Note 28.2. Air Infiltration and Ventilation Center.

AMCA. 1989. AMCA Standard 500. Test methods for louvers, dampers, and shutters. Air Movement and Control Association. Arlington Heights, IL. 60004.

Appleby, P. 1991. Environmental Criteria. Certified Industrial British Service Engineers National Conference. Canterbury, UK.

Appleby, P.H. 1988. Personal air supply as a means of improving indoor air quality and energy efficiency. Proceedings of Ventilation '88. London, UK.

Arens, E.A., F.S. Bauman, L.P. Johnson, and H. Zhang. 1990. Testing of localized thermal distribution systems in a new controlled environment chambers. Preprints of the 11th AIVC Conference. Belgirate, Italy.

ASHRAE Handbook. 1993. ASHRAE Handbook. Fundamentals. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA. 30329.

ASHRAE. 1993. Air conditioning system design manual. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA. 30329.

ASHRAE. 1989. Guideline GPC-1, Guideline for commissioning of HVAC systems. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA. 30329.

ASHRAE. 1990. ASHRAE Standard 62-1989. Ventilation for acceptable indoor air quality. ASHRAE. Atlanta, GA. 30329.

ASHRAE. 1993. ASHRAE Standard 55-1992. Thermal environmental conditions for human occupancy. ASHRAE. Atlanta, GA. 30329.

2023687751

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

ASHRAE Handbook. 1992. HVAC Systems and Equipment. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA. 30329.

Atlas Compac. 1989. Technical Literature. Creating the right office environment. Company brochure. Birmingham, UK.

Awbi, H.B. 1991b. The feasibility of high outdoor air rates for office and auditoria. Certified Industrial British Service Engineers National Conference. Canterbury, UK.

Axelrad, R. and M. Maroni, (eds). 1993. Pilot Study on Indoor Air Quality. NATO: Committee on the challenges of modern society.

Bauman, F.S., D. Faulkner, E.A. Arens, W.J. Fisk, L.P. Johnston, P.J. McNeel, D. Pih, and H. Zhang. 1992. Air movement, ventilation, and comfort in a partitioned office space. ASHRAE Transactions. 98(1):756-782.

Bauman, F.S., H. Zhang, E.A. Arens, and C.C. Benton. 1993. Localized comfort control with a desctop task conditioning systems: Laboratory and field measurements. ASHRAE Transactions. 99(2).

Breum, N.O. 1988. The air exchange efficiency of a lecture hall. Ventilating -88. 2nd International Symposium on Ventilation for Contaminant Control. Imperial College, London. 20-23 September 1988.

Brickman, H. 1989. Commissioning: why we need it - what are the benefits. ASHRAE Transactions. 95(1):881-882.

Burge, H.A. and W.R. Solomon. 1987. Sampling and analysis of biological aerosols. Atmospheric Environment. 21:451-456.

Christianson, L.L., (ed). 1989. Building systems: Room air and air contaminant distribution. American Society of Heating, Refrigerating, and Air Conditioning Engineers. Atlanta, GA. 30329.

Chung, T.W., T.K. Ghosh, A.L. Hines, and D. Novosel. 1993. Removal of selected pollutants from air during dehumidification by lithium chloride and triethylene glycol solutions. ASHRAE Transactions. 99(1):834-841.

CIBSE. 1986. Certified Industrial British Service Engineers Guides - Section B2. Ventilation and air conditioning (requirements). Certified Industrial British Service Engineers. London, U.K.

2023687752

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Clavier, H. 1993. Collaboration through partnering: The team approach to ensuring indoor air quality. Proceedings of Indoor Air '93. Helsinki, Finland.

Collett, C.W., E.M. Sterling, and T.D. Sterling. 1993. Strategies for the investigation of indoor air quality problems and findings from their implementation. ASHRAE Transactions. 99(2).

Commission of the European Communities. 1992. Guidelines for Ventilation Requirements in Buildings. Report No. 11. Directorate General for Science, Research Development. Luxembourg City, Luxembourg.

Crandell, M.S. 1987. NIOSH indoor air quality investigations: 1971 through 1987. Proceedings, Air Pollution Control Association Annual Meeting. Dallas, TX. 75260.

Croom, D.J. 1988. A comparison of upward and downward air distribution systems. Proceedings of Ventilation '88. Pergamon Press. London, UK.

Croom, D.J. and B.M. Roberts. 1981. Air conditioning and ventilation of buildings. 2nd ed. Vol. 1. Pergamon Press. London, UK.

Culp, C.H., B.C. Krafthefer, M.L. Rhodes, and M.A. Listvan. 1993. Silicon infrared sensors for thermal comfort and control. ASHRAE Journal. 35:38-42.

Cyfracki, L. 1990. Could upscale ventilation benefit building occupants and owners alike? Proceedings of Indoor Air '90. Toronto, Canada.

Danielson, P.O. 1988. Displacement Ventilation - Spreading disease or blessing. Proceedings of Ventilation '88. London, UK.

Designers' Guide. 1992. Ventilation and Air conditioning. Moscow: Stroyizdat. 3(1):1-319.

Dickson, D.J. 1985. Ventilation efficiency measurements in occupied mechanically ventilated buildings. Proceedings of the 6th AIVC Conference.

DOD. 1989. What is in it for us? What customers think about new construction. U.S. Department of Defence.

Elovitz, K.M. 1992. Commissioning building mechanical systems. ASHRAE Transactions. 98(2):543-552.

2023687753

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Ensor, D.S., A.S. Viner, J.T. Hanley, P.A. Lawless, K. Ramanathan, M.K. Owen, T. Yamamoto, L.E. Sparks. 1988. Air cleaner technologies for indoor air pollution. Center for Aerosol Technology, Research Triangle Institute. Research Triangle Park, NC. 27709-2194.

EPA. 1989. Report to congress on indoor air quality. Volume II: Assessment and control of indoor air pollution. U.S. Report No. EPA/400/1-89/001C. Environmental Protection Agency. Washington, D.C. 20460.

EPA. 1991. Building air quality: A guide for building owners and facility managers. Environmental Protection Agency. Washington, D. C. 20460. U.S. Government Printing Office.

Eto, J.H., C. Meyer. 1988. The HVAC costs of increased fresh air ventilation rates in office buildings. ASHRAE Transactions. 94(2):331-345.

Fahlen, P. 1993. Demand controlled ventilating systems - sensor tests. Air Infiltration Review. 14(3):47.

Fanger, P.O. 1972. Thermal Comfort. McGraw Hill Book Co. New York, NY. 10199.

Fanger, P.O. 1988. Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. Energy and Buildings. 12(1):1-6.

Fanger, P.O. 1988. The olf and decipol. New units established to quantify how air quality is perceived by human beings. ASHRAE Journal. 30:35-38.

Fanger, P.O. 1990. New principles for a future ventilation standard. Proceedings of Room Vent '90. Oslo, Norway.

Fanger, P.O., B.M. Ipsen, G. Langkilde, B.W. Olesen, N.K. Christensen, and S. Tanabe. 1985. Comfort limits for asymmetric thermal radiation. Energy and Buildings. 8:225-226.

Fanger, P.O., A.K. Melikov, H. Hanzawa, and J. Ring. 1988. Air turbulence and sensation of draft. energy and Buildings. 12(1).

Fanger, P.O., J. Lauridsen, P. Bluyssen, and G. Clausen. 1988. Air pollution sources in offices and assembly halls quantified by the olf unit. Energy and Buildings. 12(1):7-9.

2023687754

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Faulkner, D., W.J. Fisk, and D.P. Sullivan. 1993. Indoor airflow and pollutant removal in a room with desctop ventilation. ASHRAE Transactions. 99(2).

Fencl, F. 1993. Air filtration for IAQ control. Engineer's Digest. 93(9):14-16.

Fisk, W.J., J.Binenboym, H. Kaboli, D.T.Grimsrud, A.W.Robb, and P.J.Weber. 1983. Multi-Tracer System for Measuring Ventilation Rates and Ventilation Efficiencies in Large Mechanically - Ventilated Buildings." Lawrence Berkeley Laboratory, LBL-2020.

Fisk, W.J., R.J. Prill, and O. Seppanen. 1988. Commercial building ventilating measurements using multiple tracer gases. 9th AIVC Conference. 12-15 September, 1988. Gent, Belgium.

Fisk, W.J., D. Faulkner, and R.J. Prill. 1991. Air exchange effectiveness of conventional and task ventilation for offices. Proceedings of the ASHRAE Conference IAQ'91 Healthy Buildings, Washington, DC.

Gammage, R.B., D.L. Hansen, and L.W. Johnson. 1989. Indoor air quality investigations: a practitioner's approach. Environment International. 15:503-510.

Gorman, R.W. and K.M. Wallingford. 1989. The NIOSH approach to conducting indoor air quality investigations in office buildings. In: Design and protocol for monitoring indoor air quality. Nagda, N.L. and J.P. Harper, (eds). Philadelphia: American Society of Testing Materials. 1002:63-72.

Goyer, N. 1990. Chemical contaminants in office buildings. American Industrial Hygiene Association Journal. 51(12):615.

Goyer, N. and V.H. Nguyen. 1989. Strategy for studying air quality in office buildings. Montreal: IRSST.

Grimitlyn, M. 1982. Air distribution in enclosed spaces. Moscow: Stroiisdat.

Grimsrud, D.T., M.H. Sherman, J.E. Janssen, A.N. Pearman, and D.T. Harrje. 1980. An intercomparison of tracer gases used for air infiltration measurements. ASHRAE Transactions. 86(1):258-267.

Grimsrud, D.T. 1990. Future directions for ventilation standards. Proceedings of Indoor Air '90. Toronto, Canada.

2023687755

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Hale, R.W., P.Tan and D.E. Ordway. 1971. Experimental investigations of several neutrally buoyant bubble generators for aerodynamic flow visualization. Navel Research Reviews 24(6):19-24.

Heiselberg, P. 1987. The contaminant distribution in a ventilated room using different air terminal devices. Int. Conf. ROOMVENT '87. Stockholm, Sweden.

Heiselberg, P. 1991. Concentration distribution in a ventilated room under isothermal conditions. Air Movement & Ventilation Control within Buildings. 12th AIVC Conference. Ottawa, Canada. 24-27 September, 1991.

Hodgson, M., M. Light, C. Miller. 1993. TLVs and IAQ guidelines: Resolving the ambiguities. Workshop, Indoor Air '93. Helsinki, Finland.

Holmberg, R.B., K. Folkesson, L.G. Stenberg and G. Jansson. 1987. Experimental analysis of office room climate using various air distribution methods. Proceedings of Roomvent-87. Stockholm, Sweden.

Huvinen, T. and M. Rantama. 1987. Individual air conditioning control at open plan offices. Proceedings: Roomvent '87. Stockholm, Sweden.

Jaakkola, J.J.K., O.P. Heinonen, O. Seppanen. 1989. Sick building syndrome, sensation of dryness and thermal comfort in relation to room temperature in an office building: need for individual control of temperature. Environment International. 15:163-168.

Janssen, J.E. 1984. Ventilation stratification and air mixing. Proceedings of Indoor Air '84. Stockholm, Sweden.

Johnson Controls. 1988. Personal environments. Publication No. 2382. Milwaukee, WI. 53203.

Kelly, T.J. and Kinkead, D.A. 1993. Testing of chemically treated adsorbent air purifiers. ASHRAE Journal. 35(7):14-23.

Khandekar, S. and T. Tamblyn. 1990. Relationships between air quality and HVAC system design, operation and maintenance problems. Proceedings of Indoor Air '90. Toronto, Canada.

Kim, I.G. and H. Homma. 1992. Distribution and ventilation efficiency of CO_2 produced by occupants in upward and downward ventilated rooms. ASHRAE Transactions. 98(1)

2023687756

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Kinkead, D.A. 1990. Pleated DPPC - based adsorbers: New technology for air purification. ASHRAE Journal. 32:35-40.

Kirkbride, J., H.K. Lee, and C. Moore. 1990. Health and Welfare: Canada's experience in indoor air quality investigations. Proceedings of Indoor Air '90. Toronto, Canada.

Korte, B. 1989. Existing Buildings: Vast HVAC Resource. Heating/Piping/Air Conditioning. 61(3):57-63.

Knight, K.M., S.A. Klein, and J.W. Mitchell. 1993. Analysis of a rotary adsorbent filter for indoor air quality control. ASHRAE Transactions. 99(1):811-824.

Kranz. 1992. Company publication. Technodrant. Desc outlets. Kranz Labortories. Aachen, Germany.

Kusuda, T. 1989. Mathematical modeling. Building systems: Room air and air contaminant distribution. Atlanta, GA. 30329.

Lane, C.A., J.E. Woods, and T.A. Busman. 1989. Indoor air quality diagnostic procedures for sick and healthy buildings. IAQ 89. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA. 30329.

Lawson, C.N. 1989. Commissioning - the construction phase. ASHRAE Transactions. 95(1):887-892.

Lawson, T.V. 1978. Wind tunnel investigations. University of Indiana. Aerodynamics 3(2):177

McNall, P.E. 1975. Practical methods of reducing airborne contaminants in interior spaces. Arch. Environ. Health. 30:552-556.

McNall, P.E. 1986. Strategies: Today & Tomorrow. ASHRAE Journal. 28:37-40.

Menetrex, M. and R. Kulp. 1993. Draft final report-Developement of preliminary radon diagnostic measurement guidance and mitigation strategies for large buildings. AEERL, Research Triangle Park, NC.

Miller, K.J., D.E. Gardner, J.A. Graham, R.E.Lee, W.E. Wilson, and J.D.Bachman. 1979. Size considerations for establishing a standard for inhalible particles. J. Air Poll. Control Assoc. 29:610.

2023687757

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Miller, K.J., S.A. Beaulah, and T.R. Crumby. 1993. Odor pollution from farm buildings. In: Topic Analysis Report. Silsoe Research Institute.

Murakami, S., T. Tanaka, and S. Kato. 1983. Numerical simulation of air flow and gas diffusion in room model--correspondence between numerical simulation and model experiments. 4th Int. Symp. on the Use of Computers for Environmental Engineering Related to Buildings. Tokyo, Japan.

Nguyen, V.H. 1990. Ventilation effectiveness of different diffusers with partitions. Proceedings: Roomvent '90. Oslo, Norway.

Niemela, R., A. Saamanen, and H. Koskela. 1989. A comparison between the step-up, step-down and the pulse injection techniques for the measurements of the mean age of air. 10th AIVC Conference, Dipoli. 2:17-30.

Niemela, R., A. Lefevre, J.P. Muller, and G. Aubertin. 1990. Comparison of three tracer gases for determining ventilating effectiveness and capture efficiency. Room-vent '90.

NIOSH. 1987. Guidance for indoor air quality investigations. National Institute for Occupational Safety and Health. Cincinnati, OH.

NIOSH. 1989. Indoor air quality: selected references. Division of Standards Development and Technology Transfer. Cincinnatti: National Institute for Occupational Safety and Health. Cincinnati, OH.

NIOSH. 1989. The NIOSH approach to conducting indoor air quality investigations in office buildings. Congressional Testimony: J. Donald Millar. National Institute for Occupational Safety and Health. Washington, DC. 20460.

NKB. 1991. Indoor climate-air quality. Nordic Committee on Building Regulations Publication No. 61E. Kirjapaino Verbi Oy, Finland.

Novosel, D., S.M. Relwani, and D.J. Moschandreas. 1987. Development of a desiccant-based environmental control unit. pp 261-264. IAQ 87 Practical Control of Indoor Air Problems ASHRAE. Atlanta, GA. 30329.

Offermann, F.J. 1988. Ventilation effectiveness and ADPI measurements of forced air heating system. American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE Transactions. 94(1):694-706.

2023687758

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Olesen, B.W., M. Scholer and P.O. Fanger. 1979. Discomfort caused by vertical air temperature differences. "Indoor Climate". Danish Research Institute. Copenhagen, Denmark.

Pejtersen, J., L. Oie, S. Skar, C. Clausen, and P.O. Fanger. 1990. A simple method to determine the olf load in a building. Proceedings of Indoor Air '90. Toronto, Canada.

Persily, A.K. 1985. Ventilation effectiveness in mechanically ventilated office buildings. NBSIR 85-3208. Gaithersburg: National Bureau of Standards.

Persily, A.K. 1992. Assessing ventilation effectiveness in mechanically bentilated office buildings. Preprints: International Symposium on Room Air Convection and Ventilation Effectiveness. Tokyo, Japan. 22-24 July, 1992.

Peterson, J.E. 1992. Limitations of ambient air quality standards in evaluating indoor environments. American Industrial Hygenists Association Journal. 53(3):216-220.

Pettenkofer, M.V. 1858. Uber den Luftwechsel in Wohngebauden. Munchen, Germany.

Quinlan, P., J. Macher, L.E. Levantis, and J.E. Cone. 1989. Protocol for the comprehensive evaluation of building associated illness. In: Problem Buildings: Building Associated Illness and the Sick Building Syndrome. Cone, J.E. and M.J. Hodgson, (eds). Philadelphia: Hanley and Belfus, Inc.

Rajhans , G.S. 1983. Indoor air quality and CO_2 levels. Occupational Health in Ontario. 4,4:160-167

Ramanathan, K., V.L. Debler, M. Kosuko, and L.E. Sparks. 1988. Evaluation of control strategies for volatile organic compounds in indoor air. Environmental Progress. 7(4):240-235.

Rask, D. and J. Agarwal. 1989. Measurement techniques. In: Building Systems: Room Air and Air Contaminant Distribution. Christianson, L.L., (ed). American Society of Heating, Refrigerating, and Air Conditioning Engineers. Atlanta, GA. 30329.

Rask, D.R., C.A. Lane, and T.A. Bosman. 1990. Environmental stressors and systems deficiencies identified in problem office buildings. Proceedings, Air and Water Management Association, Annual Meeting. Pittsburgh, PA. 15290.

Robertson, G. 1988. Source, nature, and symptomology of indoor air pollutants. In: Indoor and Ambient Air Quality. Perry, R. and P. Kirk, (eds). London, U.K. Selper Press.

2023687759

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Rojeski, P.,Jr. and H. Singh. 1991. Increasing the ventilation effectiveness of multizone air handling units through improved outside air duct design. ASHRAE Transactions 97(1)

Roulet C. and P. Cretton. 1992. Field comparison of age of air measurement techniques. Air Distribution in Rooms. Vol. 3. Third International Conference Aalborg, Denmark. September 2-4, 1992.

Rowe, W.H.III. 1988. HVAC design criteria, options, selections. R.S. Means Co., Inc. Kingston, MA 02364.

Sandberg, M. 1981. What is ventilation efficiency? Building and Environment. 16(2):123-135.

Sandberg, M. 1983. Ventilation efficiency as a guide to design. ASHRAE Transactions. 89(2):455-477.

Sandberg, M. and M. Sjoberg. 1983. The use of moments in assessing air quality in ventilated rooms. Buildings and Environment. 18:181-197.

Schiller, G.E., E.A. Arens, F.C. Bauman, and C.C. Benton. 1988. A field study of thermal environments and comfort in office buildings. ASHRAE Transactions. 94(2):280-308.

Seppanen, O.A., W.J. Fisk, J. Eto, and D.T. Grimsrud. 1989. Comparison of conventional mixing and displacement air-conditioning and ventilating systems in US commercial buildings. ASHRAE Transactions. 95(2):1028-1040.

Sexton, K., M.X. Petreas, and K. Liu. 1989. Formaldehyde exposures inside mobile homes. Environmental Science Technology. 23:985-988.

Shaw, C.Y. 1984. The effect of tracer gas on the accuracy of air-change measurements in buildings. ASHRAE Transactions. 90(1a):212-225.

Shaw, C.Y., J.S. Zhang, M.N. Said, F. Vaculik, and R.J. Magee. 1993. Effect of air diffuser layout on the ventilation conditions of a workstation - Part II: Air change efficiency and ventilation efficiency.

Siliwinski, B.J., D. Kermath, M.R. Kemme, and M.R. Imel. 1991. Indoor Air Quality Management for Operations and Maintenance Personnel. U.S.A. CERL Technical Report P-91/42. US Army Corps of Engineers, Construction Engineering Research Laboratory. Champaign, IL. 61826-9005.

2023687760

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Simpson, J.B., C.A. Pettibone, and G.A. Kranzler. 1991. Temperature. In: Instrumentation and Measurement for Environmental Sciences. Henry, Z.A., G.C. Zoerb, and G.S. Birth, (eds). American Society of Agricultural Engineers, St. Joseph, MI. 49085.

Skaret, E. and H. Mathisen. 1983. Ventilation effectiveness - a guide to efficient ventilation. ASHRAE Transactions. 89(2):480-495.

Skaret, E. and M. Sandberg. 1985. Air exchange and ventilation efficiency - new aids for the ventilation industry. Norsk VVS (Norway). 7:527-534. OA Trans 2869.

SMACNA. 1990a. 3rd printing. Indoor Air Quality. Sheet Metal and Air Conditioning Contractors National Association, Inc. Chantilly, VA. 22022-1230.

SMACNA. 1990b. 3rd printing. SMACNA HVAC System Duct Design Manual. Sheet Metal and Air Conditioning Contractors National Association, Inc. Chantilly, VA. 22022-1230.

SNiP 2.04.05-91. 1992. Building Norms and Regulations. GOSSTROY. (In Russian). Moscow, Russia.

Steelcase. 1991. Office environment index summary report. Grand Rapids: Steelcase, Inc.

Sterling, D.A. 1984. Volatile organic compounds in indoor air: An overview of sources, concentrations and health effects. Indoor Air and Human Health. In: Proceedings of the Seventh Life Sciences Symposium. Knoxville, TN. 37950.

Sterling, E.M. 1989. Designing healthy buildings: The architect's role in the commissioning process. ASHRAE Transactions. 95(1):893-894.

Sterling, E.M., E.D. McIntyre, and C.W. Collett. 1987. Field measurements for air quality in office buildings: a three phased approach to diagnosing building performance problems. In: Sampling and Calibration for Atmospheric Measurements. Taylor, J.K., (ed). Philadelphia: American Society of Testing and Materials. 957:46-65.

Sterling, E., C. Collett, S. Turner, and C. Downing. 1992. Commissioning to avoid indoor air quality problems. ASHRAE Journal. 34(10):28-32.

Sterling, E., C. Collett, S. Turner, and C. Downing. 1993. Commissioning to avoid indoor air quality problems. ASHRAE Transactions. 99(1):867-872.

2023687761

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Sutcliffe, H.C. and J.R. Walters. 1990. Errors in the measurement of local and room mean age using tracer gas methods. 11th AIVC Conference. Belgirate, Italy.

Talbott, J.M. 1990. The relationship of energy conservation standards and indoor air quality standards. Proceedings of Indoor Air '90. Toronto, Canada.

Tamblyn, B.T. 1992. Commissioning: An operation and maintenance perspective. ASHRAE Journal. 34(10):23-26.

Thorstensen, E., C. Hansen, J. Pejtersen, G.H. Clausen, and P.O. Fanger. 1990. Air pollution sources and indoor air quality in schools. Proceedings of Indoor Air '90. Toronto, Canada.

Tichenor, B.A., L.A. Sparks, J.B. White, M.D. Jackson. 1990. Evaluating sources of indoor air pollution. Journal of Air Waste Management Association. 40:487-492.

Timmons, M.B., L.D. Albright, K.E. Torrance and R.B. Furry. 1980. Experimental and numberical study of air movement in slot ventilated enclosures. ASHRAE Transaction. 86(1):221-239.

Trueman, C.S. 1989. Commissioning: An owner's approach for effective operations. ASHRAE Transactions. 95(1):895-899.

Viner, A.S., P.A. Lawless, D.S. Ensor, and L.E. Sparks. 1988. Ozone generation in dc_energized electrostatic precipitators. IEEE Transactions on Industrial Applications. 28(3):504-512.

Walkinshaw, D.S. 1988. The sick building syndrome. Presentation to the Ontario Association of School Business Officails Operations, Maintenance and Construction Workshop: Indoor Air Quality

Walkinshaw, D.S. 1993. Curing sick buildings. Proceedings of Indoor Air '93. Helsinki, Finland.

Whittle, G.E. and E.M. Clancy. 1991. Evaluation of cases B, D and E - Presentation of results from measurements and simulations of test cases B, D and E. Annex 20 Research Report, Item No. 237-242.

WHO. 1984. Indoor air quality research. World Health Organization Regional Office for Europe. Euro Reports and Studies 103. Copenhagen, Denmark

WHO. 1987. Air quality guidelines for Europe. World Health Organization Regional Office for Europe. Copenhagen, Denmark.

2023687762

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Williams, T.O., and F.C. Miller. 1992. Odor control using biofilters. Biocycle. Oct. pg.72-77.

Wilson, A.G. 1990. A Canadian standard for residential ventilation systems. Proceedings of Indoor Air '90. Toronto, Canada.

Woods, J.E., P.R. Morey, and D.R. Rask. 1989. Indoor air quality diagnostics: Qualitative and quantitative procedures to improve environmental conditions. In: Design and Protocol for Monitoring Indoor Air Quality. Nagda, N.L. and J.P. Harper, (eds). Philadelphia: American Society of Testing and Materials. 1002:80-98.

Yaglou, C.P., E.C. Riley, and D.I. Coggins. 1936. Ventilation requirements. American Society of Heating and Ventilating Engineers Transactions. 42:133-162.

Yocom, J.E. and S.M. McCarthy. 1991. Measuring Indoor Air Quality: A Practical Guide. New York: John Wiley & Sons. Chichester, England.

Zeisig, H.D. 1988. Experiences with the use of biofilters to remove odours from piggeries and hen houses. Volatile emissions from livestock farming and sewege operations. New York, NY 10017.

Zhivov, A. 1990. Variable-air volume ventilation systems for industrial buildings. ASHRAE Transactions. 96(2):367-372.

Zhivov, A.M. and B.W. Olesen. 1993. Extending existing thermal comfort standards to work places. Proceedings of Indoor Air '93. Helsinki, Finland.

2023687763

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

APPENDICES

1: Participants

2023687764

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000

Industry/Research Representatives

Eric Adams
United Technologies
Research Center
411 Silver Lane
MS 129-79
East Hartford, CT 06108

John Carlton-Foss
Human Technical Systems Inc.
410 Boston Post Road
Sudbury, MA 01776

Don Bahnfleth
ZBA Inc.
36 E. 7th Street
Suite 200
Cincinnati, OH 45202

Bill Chadwick
Galson Corporation
6601 Kirkville Road
E. Syracuse, NY 13057

Steve Banos
Duke University
200 Facilities Center
Durham, NC 27708

Glen Chamberlin
U.S. Army Corps of Engineers (CERL)
P.O. Box 4005
Champaign, IL 61820

Stuart Batterman
University of Michigan
SPH-1
Room 2505
109 Observatory Drive
Ann Arbor, MI 48109-2029

Russell Clayton
Acurex Environmental Corp.
P.O. Box 13109
Research Triangle Park, NC 27709

Peter Brothers
Johnson Controls
507 E. Michigan Street
P.O. Box 423
Milwaukee, WI 53201

Howie Clavier
Interlex Group of Canada Inc.
3680 Mountain Street
H3H 2A8
Montreal, Quebec CANADA

H.E. Barney Burroughs
Building Wellness Consultancy
(NAIMA)
225 Mt. Ranier Way
Alpharetta, GA 30202

Tom Cobb
Electrostatic On-Site Services
2154 Utopia Ave.
Nashville, TN 37211

2023687765

Source: https://www.industrydocuments.ucsf.edu/docs/hhbl0000